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Installation Restoration General Environmental Technology Development

Contract No. DAAK11-85-D-0007 (Task Order 4)

Novel Technology Evaluation for Volatile Organic Compounds Emission Control

TECHNICAL REPORT

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March 1987

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Prepared for:
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
Edgewood Area, Aberdeen Proving Ground, Maryland 21010

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Novel technologies for volatile organic compound (VOC) emission control were evaluated to assess the potential for future application on emissions from USATHAMA installation restoration treatment processes. The novel technologies were compared with conventional technologies on the basis of performance and cost-effectiveness. Fluidized bed cataytic oxidation was recommended

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for a demonstration study in the near-term.   UV/ozone/catalytic
oxidation was recommended for a long-term development project.

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EXECUTIVE SUMMARY

The U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) has conducted an extensive study of installation restoration (IR) processes for removal of volatile organic compounds (VOC's) from soil and groundwater. These IR processes often result in emission of VOC's to the atmosphere. Since VOC emission control may be necessary and is, in many cases, the most expensive process component, USATHAMA has targeted VOC emission control for investigation to identify more cost-effective technologies for possible development efforts.

In June 1986, WESTON completed a technology review and letter report to USATHAMA entitled "New Technologies for Cost-Effective VOC Emission Control," which identified newly emerging technologies that may achieve more cost-effective control of VOC emissions from IR processes. The following technologies were recommended for further investigation:

(a) PURASIV carbon bead system (Union Carbide).
(b) KPR carbon fiber/incineration system (Met-Pro).
(c) Fluidized bed catalytic oxidation (ARI).
(d) Catalytic oxidation with ozone and/or UV light (Ultrox).
(e) Oil/water emulsion absorption (Nalco).

These technologies are examined in greater depth in this report to determine their potential for providing effective emission control at a lower cost than conventional technologies (carbon adsorption and fume incineration). The study includes the development of conceptual designs and a comparative evaluation of costs. The evaluation of novel technologies for potential development and implementation by USATHAMA is based on criteria which address expected performance, development, and implementability issues.

The analysis was based on application of the emission control technolgies to the following IR processes:

● Groundwater air stripping.
● In situ volalitization for soils.
● Low-temperature thermal stripping for soils.

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The results of the evaluation indicate that two of the five emerging technologies have the potential to provide good treatment performance at a lower cost than comparable conventional technologies for some IR applications. One conventional technology, carbon adsorption, continues to be competitive with emerging technologies for most applications but has the disadvantages of lower efficiencies and byproduct stream generation which requires off-site treatment/disposal. In many cases, carbon adsorption can provide adequate and cost-effective treatment.

Fluidized bed catalytic oxidation is an excellent technology where high-destruction efficiency and reliability are required. It can be cost-effective in many applications where incineration is presently used for chlorinated organics. The unit has been commercially applied by ARI for higher concentration applications and can be applied with little or no further development on a demonstration basis.

UV/ozone/catalytic oxidation holds the potential for low-cost emission control. Due to its operation at near ambient temperatures, operating costs are considerably lower than thermal oxidation processes. Fully modular, all-electric units are envisioned by Ultrox, the technology's developer. If successfully implemented, this could potentially lower implementation costs below those for all other technologies considered in this study. The pilot testing performed to date indicates that high potential destruction efficiencies are achievable, but byproduct formation occurs. This problem should be addressed in further development efforts.

The other technologies evaluated do not warrant development effort for applications of the scale investigated. If large air flow emission applications arise, the KPR/incineration process should be explored further.

WESTON recommends the following novel technologies for USATHAMA development efforts:

(a) Short-term development/demonstration: fluidized bed catalytic oxidation.
(b) Long-term development: UV/ozone/catalytic oxidation.

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1. INTRODUCTION

1.1 <u>Background</u>. The U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) has conducted an extensive study of processes which can be used for installation restoration (IR). Treatment processes for removal of volatile organic compounds (VOC's) from soil and groundwater may result in VOC emissions to the atmosphere. These treatment processes include groundwater air stripping (GWAS), in situ volatilization (ISV) for soils, and low-temperature thermal stripping (LTTS) for soils. VOC emission control measures may be necessary and, in many cases, these measures can be more costly than the soil or groundwater treatment process itself. As a result, USATHAMA has targeted VOC air emission control for investigation to identify promising existing technologies and, if necessary, to direct research and development efforts to facilitate implementation of technologies.

In June 1986, WESTON completed a technology review and letter report to USATHAMA entitled "New Technologies for Cost-Effective VOC Emission Control," which identified newly emerging technologies that may achieve more cost-effective control of VOC emissions from IR processes. The current literature on air pollution control for hydrocarbons was reviewed and numerous contacts were made with individuals in the following areas:

(a) EPA Research Project Officers
(b) University Researchers
(c) DOD Research Project Officers
(d) Commercial Enterprises

Upon review of the information gathered, the following novel technologies were recommended for further investigation:

(a) PURASIV carbon bead system (Union Carbide).
(b) KPR carbon fiber/incineration system (Met-Pro).
(c) Fluidized bed catalytic oxidation (ARI).
(d) Catalytic oxidation with ozone and/or UV light (Ultrox).
(e) Oil/water emulsion absorption (Nalco).

As presented in this report, these technologies were examined to determine potential for providing effective emission control at a lower cost than conventional technologies (carbon adsorption and fume incineration). The study included the development of conceptual designs, and a comparative evaluation of costs. The evaluation of novel technologies for potential development and implementation by USATHAMA was based on criteria which address expected performance, development, and implementability issues.

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WESTON performed this study under Contract No. DAAK-11-85-D-0007, Task Order 4.

1.2 <u>Objectives</u>. The objective of this study was to evaluate novel VOC emission control technologies. This evaluation included:

(a) Development of performance criteria.
(b) Development of conceptual designs and cost estimates.
(c) Evaluation of their performance and cost when applied to IR process emissions.
(d) Comparison of novel technologies to the conventional emission control technologies of carbon adsorption and fume incineration.

The overall purpose of the study was to identify those air emission control technologies which could be cost-effectively applied to IR process applications. This might include technologies which fall into one of the following categories:

(a) Long-term development required.
(b) Short-term development/demonstration required.
(c) Established technology for these applications - no further development required.

The analyses performed herein were intended to provide a balanced comparison of technologies which range from purely conceptual to established commercial technologies. Accordingly, the ability to project costs and performances varied widely. The bases for comparison of emission control technologies were emission sources from IR processes applied to sites which had been studied previously. However, the results of this study may be used to initiate air emission control technology development efforts for eventual implementation on other IR sites and possibly other IR process applications. Therefore, the concept level costing procedures exclude some cost components which are common to all VOC emission control applications (e.g., permitting) and those which are specific to siting. These cost components were both difficult to project in a concept-level analysis and were not found to aid in decision making for technology development efforts. Thus, the comparative analyses presented herein which should not be applied for budgetary projections or purposes other than selection of technologies for development without further consideration of site conditions, implementation options, and the results of development studies.

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1.3   Approach.   The evaluation of emission control technologies was based on air emissions from IR treatment processes which have been or could be applied at Army installations. The four applications were:

(a)   GWAS at Sharpe Army Depot (SHAD) - Lathrop, California.
(b)   ISV for soil at Twin Cities Army Ammunition Plant (TCAAP) - New Brighton, Minnesota:
       -    Site D
       -    Site G.
(c)   LTTS for soil at Letterkenny Army Depot (LEAD) - Chambersburg, Pennsylvania.

The most current information regarding these air emission sources was reviewed to develop the conceptual design basis.(1-6) Conceptual design process descriptions and process schematics were developed for each emerging emission control technology. Fume incineration and carbon adsorption alternatives were also used for comparison to determine whether any of the emerging technologies have significant performance and/or cost advantages over conventional technologies. Cost and performance data were requested from vendors of air pollution control equipment and firms developing and/or marketing the novel technologies. These data were used as input to develop cost estimates for the conventional and novel technologies.

The wide scope of the study covers numerous emission control technologies, each of which were analyzed for four potential IR treatment process applications. In addition, numerous implementation options are available for such technologies as carbon adsorption and incineration. To limit the number of cases analyzed to a manageable number, some assumptions were made and implementation options were selected for each technology. These are detailed in subsequent sections.

The anticipated duration of operation varies from 10 months for the ISV Site D application to approximately 10 years for the GWAS application. For shorter applications, it may be desirable to develop portable control processes which can be readily moved from site-to-site. The design of a portable unit would have increased the level of detail and complexity of the analysis and the potential for reuse of control equipment under similar operating conditions has not been established. As a result, cost estimates were based on single use of shop-fabricated, modular units which would minimize installation and tear down efforts whenever possible. Transportability was also addressed as a criterion in the technology evaluation.

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Capital costs were developed based on major equipment costs and installation factors. Written quotes were obtained where possible; when unavailable, verbal estimates were used to provide basis for comparative evaluation. Operating cost assumptions were based on the locale of the anticipated remedial action or a percentage of capital cost. Capital and operating costs are presented for each technology in Section 3. The comparative evaluation in Section 4 includes a net present worth analysis based on the anticipated duration of operations, and a cost per ton of emissions abated. A more general analysis of the effects of emission source flow rate and duration of operations was also conducted to provide a basis for considering other applications of these technologies.

Finally, the technologies were evaluated and then compared on the basis of the following criteria representing important development and implementation issues:

(a) VOC control efficiency.
(b) Ease of operation/maintenance.
(c) Reliability.
(d) Transportability.
(e) Environmental issues.
(f) Development time.
(g) Proprietary status.
(h) Projected treatment costs.

Based on this evaluation, recommendations were made on which technologies to select for application and/or development efforts.

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2. PROFILE OF EMISSION SOURCES

The evaluation of volatile organic compound (VOC) emission control technologies was made on the basis of planned or actual emission sources from various treatment processes currently under development by USATHAMA. This section provides a description and emission source profile (design basis) for each source considered.

2.1 In Situ Volatilization (ISV).

2.1.1 Process description. The ISV technology was demonstrated in a pilot study conducted by the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) in 1984 and 1985 at Site D of the Twin Cities Army Ammunition Plant (TCAAP), located in New Brighton, Minnesota. The process is presently being applied in two full-scale remedial operations at TCAAP. The two sites where ISV is being applied, Site D and Site.G, are former waste burn/disposal areas which contain soils contaminated with trichloroethylene, trichloroethane, and small quantities of other chlorinated VOC's.

The ISV system removes VOC's from the soil by mechanically drawing air through the soil pore spaces. An array of vents is installed in the contaminated portion of the unsaturated (vadose) zone. The vents are manifolded to air blowers which create a negative pressure in the system and pull air from the soil. Each vent is valved and can be adjusted to the desired flow rate. A general schematic of the ISV process is shown in Figure 1.

2.1.2 Design basis for air emission control. ISV VOC emission sources were characterized based on actual operating data.(2,3) Site D has been operational for the longest time, while Site G operation was suspended after approximately 1 week. The ISV system operation air emission data shows declining emission rates over time. To develop design bases for Site D and Site G effluent streams, best fit decay curves were developed to project emission rates beyond the available data base for ISV operations.

Emission data for Site D were plotted showing total VOC's versus days of operation (Figure 2). The plot suggests an exponential decline in total VOC emissions which could be predicted by an equation of the type $M = M_o (e^{-kt})$, where M represents the VOC emission rate, M_o is the initial VOC emission rate, t is time, and k is an empirical constant. This equation was converted by logarithmic transformation into a linear form. The natural log of the total VOC emission rate was then used in a linear regression with the days of operation. The final result was the following equation:

$$M = 753.7735 (e^{-0.02335t}).$$

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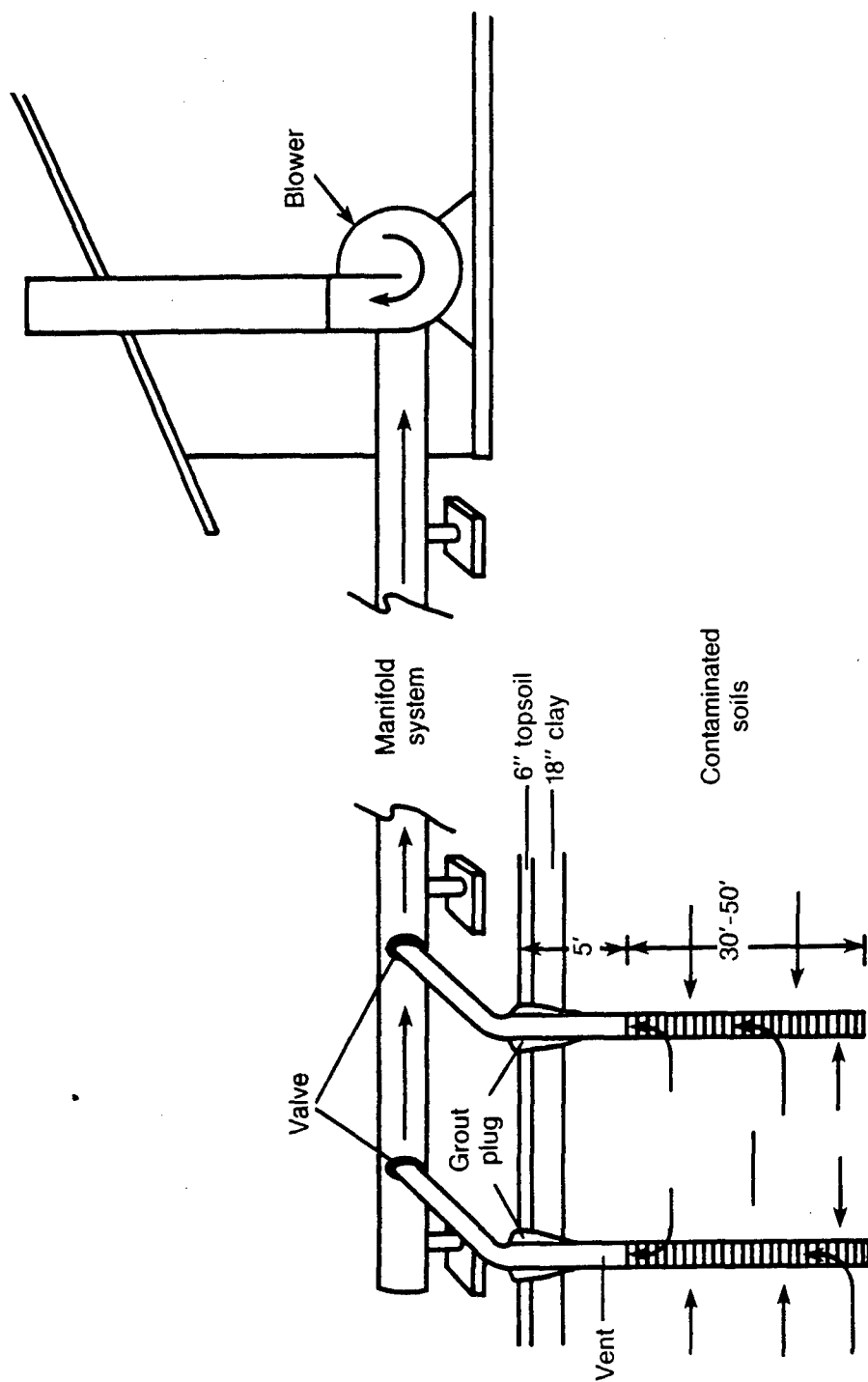
Figure 1.   In-situ volatilization schematic diagram.
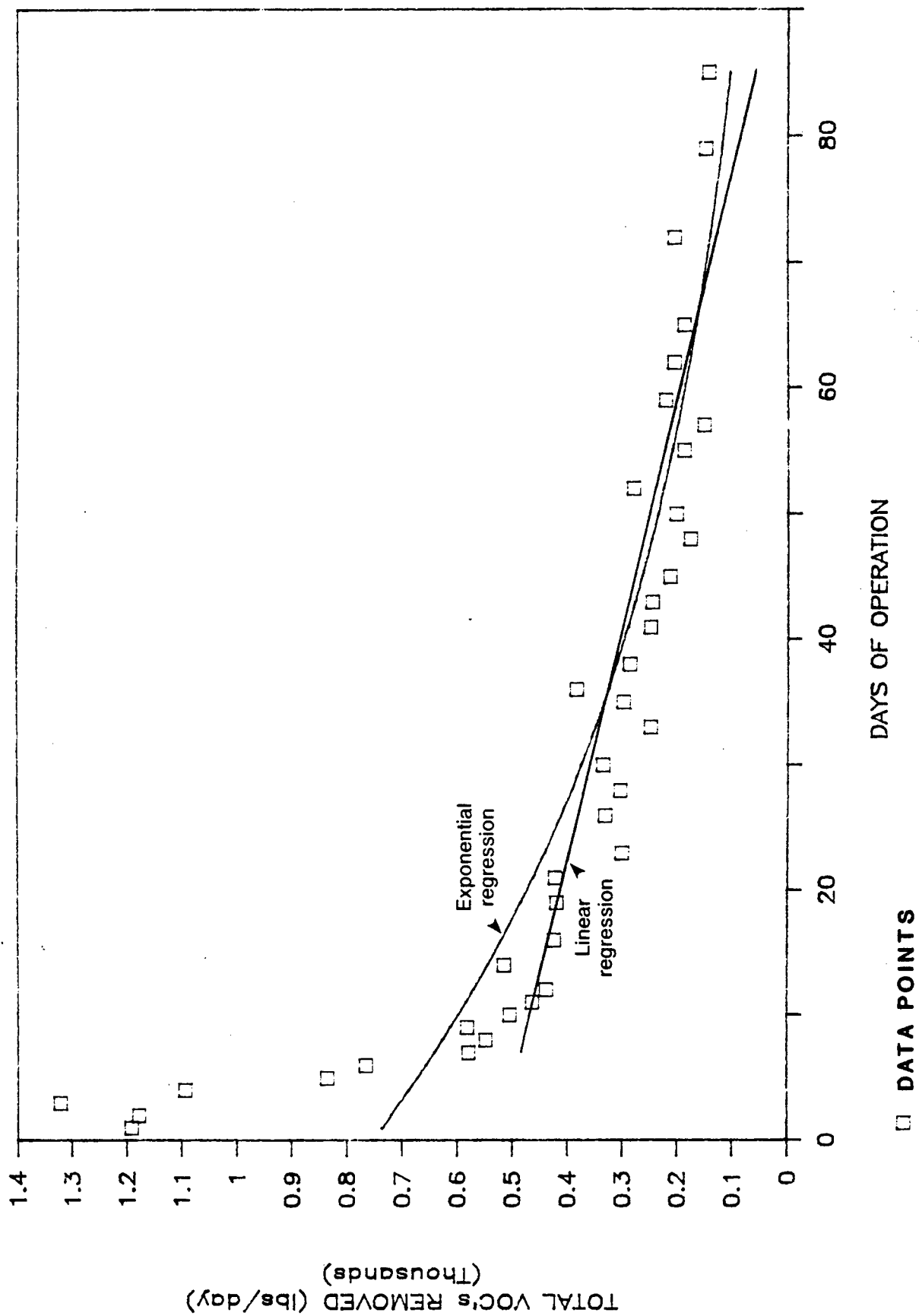
Figure 2. VOC emissions from TCAAP Site D.

This curve is plotted in Figure 2. A linear regression of the untransformed data was also performed (M versus t) and is also shown in Figure 2. The exponential curve had a higher correlation factor and was determined to be a better fit.

Data collected during the short period of operation at Site G indicated that VOC emissions declined, but the length of operation was too short to make reliable projections.(2) In addition, with the exception of the first day, the Site G system was operated with less than one-tenth of the total extraction vents open due to the high output of VOC's. While the vents containing the highest concentration of VOC's remained open, this cannot be regarded as representative of the total system emissions when run at or near capacity. As a result, it was necessary to use another method to project emissions from unthrottled long-term operation at Site G.

While emissions were higher at Site G, it was assumed that the emission rate decay overtime would exhibit behavior similar to that for Site D. As a result, the shape of the curve, and thus, the exponential decay constant (k), from Site D was used. The value used for the initial VOC emission rate (M_o) in the exponential decay equation $M = M_o (e^{-kt})$ was 2772.9 lb/day; the emissions measured for the first day of operation at Site G.(2) Thus, the initial emission rate from Site G, combined with the exponential/decay rate from Site D was used to project the Site G emissions under unthrottled conditions. This results in the following equation:

$$M = 2772.9 (e^{-0.02335t})$$

to represent the Site G total VOC emissions over time.

These projected emission profiles represent an extrapolation from existing data based on empirical equations. Since a theoretical method of predicting ISV behavior has not been developed, these projections represent what is believed to be a best estimate of ISV emissions.

Table 1 outlines the design basis emissions for the ISV air streams to be treated. The maximum concentrations were determined from the emission data during the first few days of operation. Operating life was based on the projected time to reach 1 pound per day of emissions. The average emissions were determined by calculating the cumulative projected total emissions (based on the exponential curve) and dividing by the number of operating days. The minimum concentrations were calculated assuming that emissions will require control until VOC emissions drop to below 1 pound per day. Relative humidity and air flow rate were based on actual operating conditions.

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TABLE 1. DESIGN BASIS EMISSIONS FOR ISV SITES D AND G

	Operational parameters					
	Air Flow Rate	Relative humidity (%)	Air tempera-ture		Operating life	Projected total VOC's (during) operating life)
	acfm m³/min		°C	°F		
Site D	3,200 90.6	80-100	10	50	10 months	16.1 tons
Site G	7,300 206.7	100	10	50	1 year	59 tons

	Contaminant	Air emission concentration (mg/m³)		
		Maximum	Average	Minimum
Site D	Trichloroethylene	4,676	316	2.8
	1,1,1-trichloroethane	1,187	79	0.7
Site G	Toluene	366	10	0.03
	1,1,2-trichloroethylene	5,698	315	0.9
	1,1,1-trichloroethane	1,632	105	0.3
	Cis-1,2-dichloroethylene	1,427	81	0.2
	1,1-dichloroethane	305	18	0.05

2.2 Low Temperature Thermal Stripping (LTTS).

2.2.1 Process description. The LTTS system treats soils contaminated with VOC's in a thermal processor which uses indirect heat exchange to heat and dry the contaminated soil. The effect of heating the soil is to evaporate most of the VOC's. A carrier gas (i.e., air or nitrogen) is introduced to the unit to enhance VOC removal. In the present design, the VOC's in the off-gases are thermally destroyed in an afterburner. It is this inlet stream to the afterburner which is the subject of investigation of alternative emission control technologies.

LTTS was demonstrated in a pilot study at Letterkenny Army Depot (LEAD), located in Chambersburg, Pennsylvania, during August and September 1985 on the soils in Area K-1.(5) These soils are contaminated with trichloroethylene, trans-1,2-dichloroethylene, tetrachloroethylene, and xylene. In June 1986, an economic evaluation of LTTS implementation options was conducted.(6) It analyzed four full-scale LTTS systems of the following soil treatment capacities:

    (a)   System A - 90 tons per day.
    (b)   System B - 183 tons per day.
    (c)   System C - 366 tons per day.
    (d)   System D - 732 tons per day.

System B was found to be the most cost-effective for sites having from 15,000 to 80,000 tons of soil to be treated. A general schematic of the full-scale LTTS process is presented in Figure 3.

2.2.2 Design basis for air emission control. The assumptions used to construct the design basis for this technology were based on source data and options selected (e.g., System B as described above) for implementation in the economic evaluation of LTTS implementation options.(6) For our purpose of this study, it is assumed that Area K-1 within the East Patrol Road disposal area, where the pilot study was conducted, would be the contaminated area to be treated. The LEAD remedial investigation/feasibility study report (4) describes this area as confirmed source Area No. 2 within Area K-1. This area has dimensions of 200 feet x 75 feet x 22 feet. At the soil density of 91 pounds per cubic foot for site soils, the total amount of soil to be treated is approximately 15,000 tons.
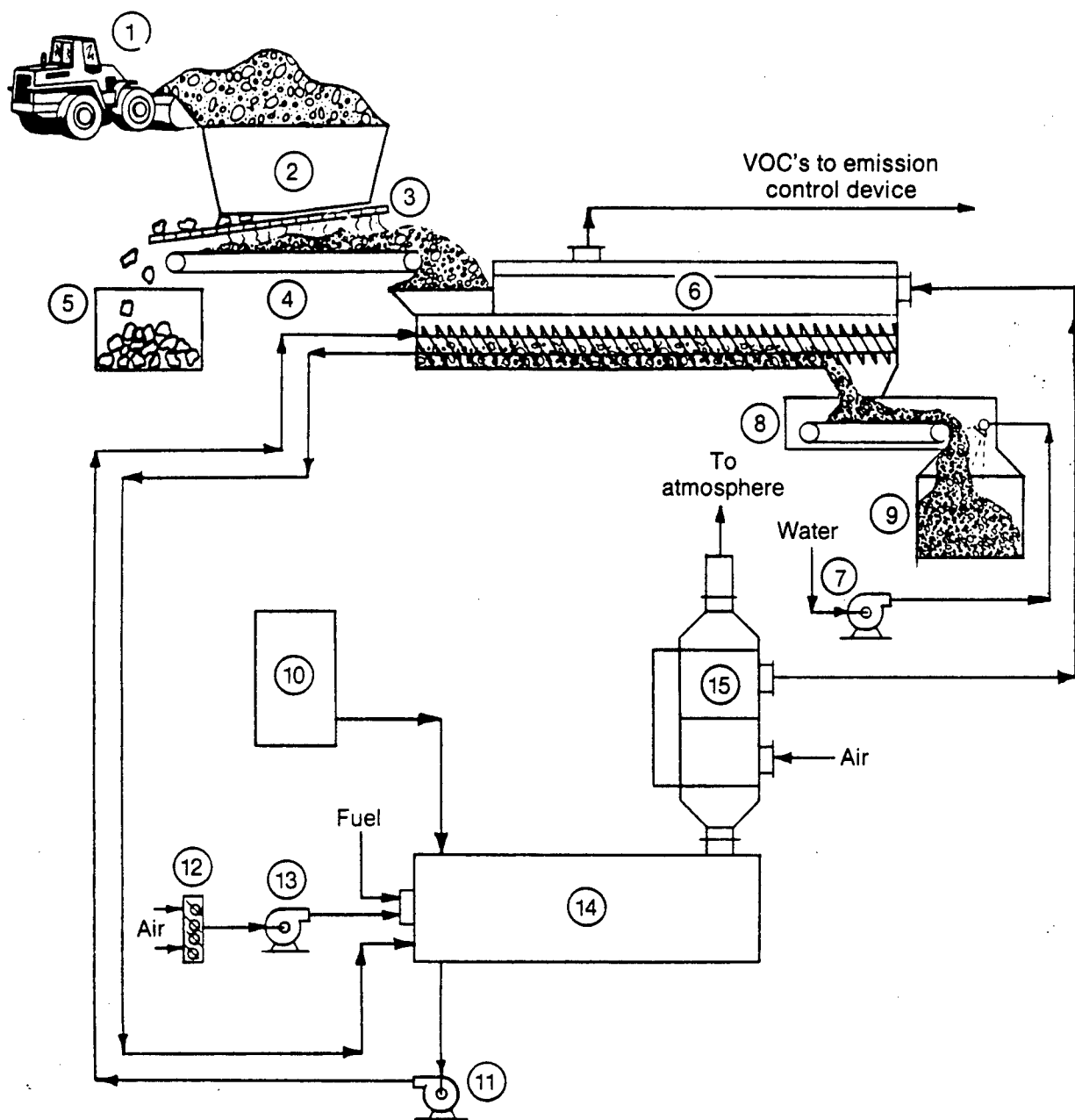
Legend

1	Front end loader	6	Thermal processor	11	Hot oil pump
2	Feed hopper	7	Water spray pump	12	Louvre damper
3	Vibrating screen	8	Belt conveyor	13	Combustion air fan
4	Belt conveyor	9	Processed soil hopper	14	Oil heater
5	Reject hopper	10	Oil reservoir	15	Air-to-air heat exchanger

Figure 3.   Schematic diagram of the low temperature thermal stripping system.

Estimates of air emissions concentrations were based on the assumption of 100-percent transfer of VOC's from the soil to the air flow projected for System B (1,864 acfm). The maximum VOC concentrations found in the soil were given in the pilot study report (5) as greater than a particular concentration value. For the purposes of this study, these VOC concentration values are assumed to be the maximum concentration in soil and were used to calculate the maximum concentration of VOC's in the air emissions. The average VOC concentration in air emissions were estimated based on the average soil concentration. It was assumed that the site remediation criterion for VOC contaminants in soil would be at or above 1 mg/kg. As a result, minimum VOC concentrations in air emissions were estimated based on a soil concentration of 1 mg/kg.

The design basis for alternative emission control technologies for LTTS is presented in Table 2.

2.3 Groundwater Air Stripping (GWAS).

2.3.1. Process description. The Sharpe Army Depot (SHAD) located in Lathrop, California provided maintenance services for vehicles, aircraft, industrial, and medical equipment from 1941 to 1975. Organic solvents were used in these operations for degreasing, paint stripping, and paint spraying. Spent solvents and sludges from these operations were land applied. According to an environmental contamination survey conducted in February 1985, the concentration of trichloroethylene in groundwater downgradient of the SHAD boundary exceeds the State of California criteria for trichoroethylene in groundwater of 5 micrograms per liter (ug/L).(1)

Packed column air stripping is being considered by the U.S. Army as an alternative for treatment. In a countercurrent packed column, water is pumped to the top of the tower and spread over packing material. The packing is designed to provide a high surface area for air/water contact as the water falls through the tower. Air is blown through the bottom of the tower and passes across the water and through the packing. The rate of mass transfer (of solute from the water to the air) is greatest when the concentration of solute in the water is high and the concentration in the air is low. A generalized process schematic of the SHAD pilot air stripper is presented in Figure 4.

2.3.2 Design basis for air emission control. The source study for this design basis was a pilot demonstration of air stripping of groundwater contaminated with VOC's at SHAD, completed in February 1985.(1) The study presented a wide range of options for GWAS implementation without recommending a preferred one. As a result, several assumptions were made, upon

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TABLE 2.   DESIGN BASIS EMISSIONS FOR LTTS

Operational parameters		
Air flow rate:	1,864 acfm	52.8 m³/min
Relative humidity:	24.5%	
Air temperature:	119°C	247°F
Operating life:	1 year	
Projected total VOC's removed:	29 tons	

Contaminant	Air emission concentration (mg/m³)		
	Maximum	Average	Minimum
Trans-1,1-dichloroethylene	2,840	250	0.6
Trichloroethylene	7,645	485	1.1
Tetrachloroethylene	8,300	210	0.5
Xylene	103	15	0.04

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Figure 4. Groundwater air stripping schematic diagram.
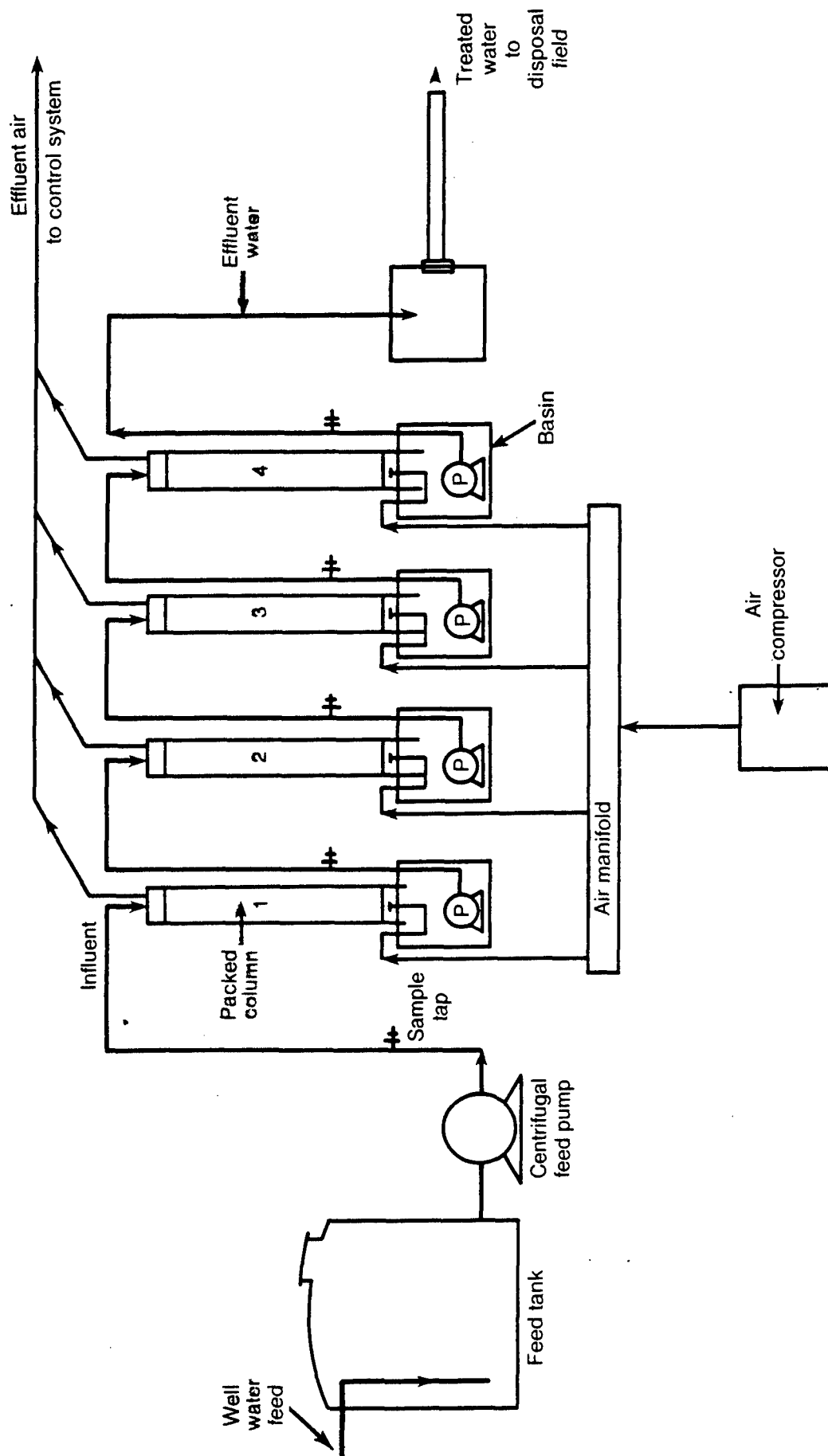
*Source: Draft final report for pilot demonstration of an air stripping technology for the treatment of groundwater contaminated with volatile organic compounds at Sharpe Army Depot.
Prepared by: Environmental Science and Engineering, Inc.
Prepared for: U.S. Army Toxic and Hazardous Materials Agency, February 1985.

consulting with USATHAMA, to determine the design basis for this effluent stream. The air stripper was assumed to have a water flow rate of 200 gpm and an air-to-water ratio of 30:1. The operational life time was estimated at 10 years. Finally, the effluent air was assumed to have a 100-percent relative humidity and a temperature of 77°F. The design basis is presented in Table 3.

2.4 <u>Overview of emission sources</u>. All of the emissions from the various treatment technologies can generally be characterized as containing low-to-moderate concentrations (averaging between 50-1000 mg/kg of total VOC's) of volatile chlorinated hydrocarbons and having a relatively low air flow rate (between 800 and 7300 acfm). Lower concentrations result in lower recovery efficiencies using recovery technologies (e.g., carbon adsorption). Both low air flow rates and low concentrations generally result in less cost effective treatment, as measured in cost per ton of emissions abated for all technologies.

The contaminants are primarily chlorinated hydrocarbons, many of which are regulated under state VOC emission control regulations. Some of these contaminants may also be regulated under state air toxics regulations. The emission control performance requirements under these regulations vary by state, local, and in some cases, by site-specific projected ground level concentrations. Thus, performance objectives for VOC control of these sources would depend on site selection.

Emission control approaches using oxidation typically result in byproduct HCl emissions. HCl emission control regulations also vary by location but off-gas treatment may be necessary in some cases for acid removal. This would typically increase the overall cost of emission control.

The anticipated lengths of operation for ISV and LTTS applications at TCAAP and LEAD were estimated at 1 year or less within the context of this study. This is shorter than the typical industrial emission control system operating life and would result in capital costs comprising a greater percentage of overall cost than operating costs. If the emission control technologies for ISV and LTTS were transportable, reuse of the equipment at other sites could reduce the cost of treatment at each site.

GWAS applications typically require long-term operation, similar to the 10 years assumed for the SHAD site. Therefore, the incentive for making these units transportable is not as great as for a short duration operation.

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TABLE 3. DESIGN BASIS EMISSIONS FOR GWAS

Operational parameters		
Air flow rate:	800 acfm	22.66 m^3/min
Relative humidity:	100%	
Air temperature:	25°C	77°F
Operating life:	10 years	
Projected total VOC's removed:	0.87 tons per year	

	Air emission concentration (mg/m^3)		
Contaminant	Maximum	Average	Minimum
Trichloroethylene	100	50	25
Chloroform	2	1	0.5
Trans-1,1-dichloroethylene	10	5	2.5
1,1-dichloroethane	20	10	5

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3. EVALUATION OF TREATMENT TECHNOLOGIES

3.1 Evaluation methodology.

3.1.1 Evaluation criteria. A comparative evaluation of five emerging treatment technologies and two established technologies was conducted. The evaluation conducted was based on the following criteria:

(a) VOC control efficiency - Actual or expected performance based on results available in commercial applications, technical literature and/or engineering judgment.

(b) Reliability - Ability of the technology to achieve a consistent control efficiency at a fixed operating condition and under variable contaminant loadings.

(c) Ease of operation/maintenance - The system should be operated with a minimum of operator attention. Operators should not require extensive specialized education.

(d) Transportability - The expected operational life of ISV and LTTS remediation efforts are relatively short (10 months to 1 year). While these durations do not necessarily require "portable" equipment ready to move on a day-to-day basis, the equipment should be readily reusable to provide for recovery of capital investment over the useful life of the equipment. The technology should be capable of modular construction with a minimum of field erection and tear down effort required.

(e) Environmental issues - Permitting or other regulatory issues may impact or prevent implementation. By-product or waste product emissions and off-site disposal of process waste streams should be considered.

(f) Proprietary status - A technology is more desirable if it is in the public domain and less desirable if it is proprietary and protected by patents. Proprietary technologies would require close cooperation with the sponsoring company to proceed with development and application.

(g) Development time - Approximate time required for development and application. Technologies with short development time requirements are more desirable.

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(h) Estimated treatment costs - Estimated capital and operating costs were developed for each technology. Total costs over the life of the project were expressed as net present worth. Costs were also expressed as $/ton of emissions abated.

3.1.2 Methodology for cost estimation. Cost projections were made for seven technologies (including one to three options for each technology) applied to each of four treatment process emission applications. The level of development for these technologies ranges from established commercial systems to purely conceptual systems. Accordingly, simplified cost estimating techniques were used commensurate with the accuracy required for a comparative evaluation of technologies.

Whenever possible, capital cost estimates were based on written equipment quotes. For technologies where written quotes were not available, verbal estimates were obtained to provide some basis for evaluation of the technology. Those "order-of-magnitude" cost estimates which involved a higher degree of uncertainty are clearly distinguished in this report.

Total installed capital costs were estimated using major equipment costs and installation factors and did not include site specific considerations. The use of installation factors for this level of analysis is an accepted technique and adequate for the objectives of the study. However, the limitations of this approach should be noted. Capital costs were not based on specific siting considerations and should not, therefore, be used for budgetary projections or purposes other than for the selection of development technologies. Specific siting requirements, such as long utility connections or no available connections, are not reflected in the estimate. The availability of support facilities and buildings was unknown and provisions for their construction was not included. Some installation cost components which were not common to most projects, such as engineering and short-run utility connections, may not linearly decrease with equipment cost on the low end of the cost spectrum. As a result, this methodology may uniformly underestimate total installed cost for smaller sized, lower equipment cost applications. Thus, these cost estimates should primarily be utilized in the context of the study to provide the cost comparisons required to identify promising technologies for future development efforts.

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Installation factors of 1.6 to 2.0 are typically used to estimate total installed cost for incineration and modular carbon adsorption units on developed plant sites. Anticipated applications on Army Installations would be in remote locations which lack local utilities and support facilities. This will result in higher installation costs relative to major equipment costs. Therefore, a higher installation factor of 2.5 was used for each technology to better represent probable costs in these applications, unless otherwise noted.

Operating cost estimates were based on unit prices specific to the installations (LEAD, SHAD, TCAAP) used for the design basis. Since maintenance requirements are not well defined for the newer technologies, annual maintenance costs were uniformly estimated at 6 percent of installed capital cost. Other general assumptions used for cost estimating are listed in Table 4. Unit cost assumptions for LEAD, SHAD, and TCAAP are listed in Table 5.

Transportable or portable equipment is desirable for the ISV and LTTS applications due to the expected short-term operation. For the purposes of this study, cost estimates were based on reusable fixed installations (i.e., shop-fabricated, skid-mounted modular units) for the following reasons:

(a)   Some technologies are not undeveloped enough to design mobile units.

(b)   For others, design and cost estimating for mobile units would require detailed engineering efforts beyond the scope of this study.

(c)   The sites and design characteristics for future reuse are not yet known.

Permit requirements for the various technologies are site-specific and were difficult to predict due to the complexity and variability in the application of air pollution control regulations by the states. For example, in ozone nonattainment areas, lowest achievable emission rate (LAER) requirements may be applied. For attainment areas, prevention of significant deterioration (PSD) requirements, including implementation of the Best Available Control Technology (BACT) may be applied. This would entail a facility definition of the facility boundaries, detail of other emission sources on the facility, and evaluation of contemporaneous emission increases at the site for the last 5 years.

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TABLE 4. COST ESTIMATION ASSUMPTIONS

General

Propane used where a fuel source was necessary.

Where utilities are required (i.e., electricity), no costs for long-distance connections included.

An on-site wastewater treatment plant was not available for handling wastewaters from the emission control equipment.

Optional process control or safety monitoring equipment was not included in the cost.

Shop-fabricated modular units were considered where possible. These units would be designed to minimize field assembly and disassembly efforts.

Specific permitting costs were not included with the exception of a stack test with an estimated lump sum cost of $15,000.

The air emission control equipment would be operated by the facility operating contractor's personnel.

The air emission control equipment malfunction shutdown instrumentation would be connected via interlocks to the IR treatment process (ISV, LTTS, or GWAS). The entire system would be shutdown in the event of equipment failure. Therefore, 24-hour per day operator attention would not be necessary.

Total costs were rounded to the nearest $1,000 and are presented in 1986 dollars.

Capital cost installation factor

This _includes_ emission control equipment, standard auxiliary equipment, instruments and controls, foundations and supports, assembly, local electrical/utility hookups, routine site preparation, engineering and supervision, construction and field expenses, and construction fee.

This does not include unusual facility site-specific preparation costs, support facilities and buildings, start-up assistance, and performance testing.

TABLE 4. (CONTINUED)

Carbon adsorption

Carbon would be regenerated on-site using steam. However, since steam would not be available at the site due to remote location; a package steam boiler was included in capital cost.

Activated carbon has 4 to 6 years of life.

Adsorption isotherm data was extrapolated to low contaminant concentrations.

Periodic monitoring of the treated air for VOC breakthrough would be necessary.

Average concentrations of contaminants and isotherms were used to calculate regeneration frequencies and, therefore, quantities of steam, propane, and water needed; volumes of water tanks, receiver tank; and amounts of wastewater and solvents requiring disposal.

Fume incineration

Emission control from remediation process would not be a RCRA hazardous waste incinerator.

Destruction efficiencies of 99 percent were used for cost estimates.

Standard combustion monitoring included. No specialized continuous monitoring equipment, as would be required for a RCRA hazardous waste incinerator, were included.

Seventy-five percent efficient heat exchanger was used.

PURASIV/Carbon Bead

Order-of-magnitude cost estimate based on telephone communication with Union Carbide.

Equipment cost of at least $300,000 due to complexity of the process.

Extensive detailed design costs necessary to scale-down the process from available equipment sizes were not included.

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TABLE 4. (CONTINUED)

PURASIV/Carbon Bead (continued)

Operating carbon capacity of 1 to 2 percent.

Carbon beads have an attrition rate of 5 percent per year.

Condensed VOC would be a hazardous waste and would be disposed off-site by incineration, at a commercial RCRA facility.

Periodic effluent monitoring would be necessary due to changing concentrations over time.

KPR Carbon Fiber/Incineration

Estimates based on written quote for 10,000 and 20,000 cfm air flows containing a generic "low concentration" VOC influent stream with no heating value.

Exponential scale-up/scale-down factor was used to extrapolate from 10,000 and 20,000 cfm cases to the four study cases to estimate capital cost.

Fuel cost assumed linearly proportional to air flow rate.

Periodic monitoring of effluent from KPR carbon unit would be necessary due to changing inlet concentrations.

Catalytic oxidation

Emission control for remediation process would not be a RCRA hazardous waste incinerator.

Destruction of 99 percent used for cost estimates. Lower or higher efficiencies achievable by varying temperatures downward or upward.

Standard combustion monitoring included. No specialized continuous monitoring equipment, as would be required for a RCRA hazardous waste incinerator, were included.

Forty-two percent efficient heat exchanger was used. This allowed for the maximum heat recovery possible while remaining above the dew point of HCl.

Catalyst life is 2 years.

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TABLE 4. (CONTINUED)

UV/ozone/catalytic oxidation (Ultrox)

Order-of-magnitude cost estimated based on communication with Ultrox.

Costs based on similar UV/ozone water treatment system components and ozone utilization estimates by Ultrox in the absence of performance data for the VOC compounds of interest.

Exponential scale-up factor for equipment based on scale-up factor for ozone generator, the largest component cost.

Power consumption estimated at 0.4 kw hr/1,000 scf.

Oil/water emulsion absorption (Nalco)

Technology not costed due to technical limitations.

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TABLE 5. FACILITY SPECIFIC OPERATING COST ASSUMPTIONS

Cost component	Installation		
	TCAAP	LEAD	SHAD
Operating labor ($/manyear)	40,000	40,000	40,000
Supervision (% of operating labor)	25	25	25
Propane ($/gallon)	0.50	0.41	0.45
Power ($/kw hour)	0.04	0.06	0.06
Incineration of recovered solvent ($/pound)	0.42	0.42	0.42
Mileage to off-site RCRA commercial incinerator (Chicago)	400	785	2,200
Transportation cost to incinerator ($/loaded mile)	3.50	3.50	3.50
Treatment/disposal charges of condensed water ($/gallon)	.25	.25	*
Mileage to off-site commercial treatment/disposal facility	400	300	*
Transportation to treatment/disposal facility ($/loaded mile)	4.00	4.00	4.00
Stack test monitoring (particulates, NO_x, HCl, organics)	$15,000	$15,000	$15,000
Carbon, KPR, and PURASIV weekly bag sample monitoring ($/year based on $350/sample)	18,000	18,000	18,000
Caustic supply (20% NaOH):			
Material cost ($/dry ton)	180	175	200
Transportation cost ($/100 pounds)	1.20	0.50	1.50

*Condensed water will be recycled to the GWAS.

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Due to the level of detail needed to adequately address the permitting process for each case, full permit-related costs were excluded from the cost estimates for all technologies. One permit related requirement which can be projected for all applications is an initial stack test for VOC, particulates, CO, and NO_x. The cost for stack testing, estimated at $15,000, is included in the capital cost for each technology.

A summary of the cost estimates is presented for each technology in this section. Additional details for each estimate are provided in Appendix A. The costs are then compared in Section 4. A net present worth analysis is used in Section 4 to consider both operating and capital cost over the expected life of the installation; all costs are represented in 1986 dollars using 10 percent annual interest. Emission control cost effectiveness measured as dollars per ton of emissions abated is also calculated and presented in Section 4.

3.2 Carbon adsorption.

3.2.1 Process description. Carbon adsorption is an established commercial technology used for VOC emission control. Adsorption is a surface phenomenon in which molecules of a liquid or gas adsorb onto and accumulate on the surface of a solid. The extent of adsorption is proportional to surface area and the properties of the solid adsorbent and the fluid.

The most widely used and generally the most cost-effective adsorbent for removal of organic compounds from water and air is activated carbon. The characteristic physical property of activated carbon which enhances its adsorption capacity is its extremely large surface area, approximately $1,000. \ m^2/g$. Adsorption is effective for a wide range of contaminant concentrations. In general, carbon will adsorb most organic compounds from exhaust fumes with molecular weights over 45.

Activated carbon adsorption systems typically use granular activated carbon in a fixed bed. Operation is usually on an alternating cycle of adsorption and regeneration. Multiple vessels may be used if continouous operation is necessary for the application.

There are many regeneration options for spent carbon. They include:

(a) Steam regeneration.
(b) Pressure swing (vacuum regeneration).
(c) Indirect heating.
(d) Hot air regeneration.
(e) Inert gas regeneration.
(f) Thermal regeneration.

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The steam regeneration system is typically used for the regeneration of spent carbon containig immiscible solvents such as toluene, xylene, and benzene. Vacuum, indirect heating, hot air, and inert gas regeneration techniques are more suitable for carbon containing high vapor pressure, water soluble solvents. Thermal regeneration, using multiple hearth furnace and afterburner, is only cost-effective for extremely high quantity carbon use applications.

A method of spent carbon regeneration which has been cost-effective for very low carbon utilization applications is the transportation of spent carbon to an off-site thermal regeneration facility. The VOC's are removed from the carbon and destroyed in an afterburner at the regeneration site. The regenerated carbon can then be returned to service. Since this approach is more expensive for the larger applications studied here, the off-site regeneration option was not selected for this evaluation.

Since the contaminants of concern are immiscible chlorinated hydrocarbons, they should be separable from water. As a result, steam regeneration, the most widely used on-site regeneration option, was selected as the regeneration made for the carbon adsorption technology. Steam would be used to heat the bed of spent carbon and purge desorbed organics into a condensor. Aqueous and organic phases would be decanted and collected for disposal. Chlorinated organic liquids cannot be landfilled and there is little commercial demand for small quantities of mixed solvents. Therefore, it was assumed that the solvents would be disposed of off-site by incineration at a commercial facility. The aqueous phase would be contaminated up to the solubility limits with VOC's. Since the availability of on-site wastewater treatment capacity and the ability to obtain approval for discharge to a publicly-owned treatment works (POTW's) are uncertain, it was assumed that water collection and off-site treatment/disposal would be necessary.

3.2.2 Conceptual design. A general schematic of an activated carbon system is provided in Figure 5. An air blower conveys the solvent-laden air through the carbon adsorber unit. The treated effluent air is released via the stack. After the capacity of an adsorber unit is spent, the influent air is directed to the second adsorber unit. Regeneration steam is then introduced to the first carbon unit. The steam and solvent vapor are collected and directed through a condenser. The condensed liquid solvent and water are separated in a decanter. The water will contain some solvent at low concentrations, depending on its solubility. This water may be recycled to the air stripper in the case of the SHAD groundwater air stripping unit as long as concentrations remain high enough to achieve phase separation of water and organics. For the other systems, off-site treatment/disposal will be required for the condensed water.

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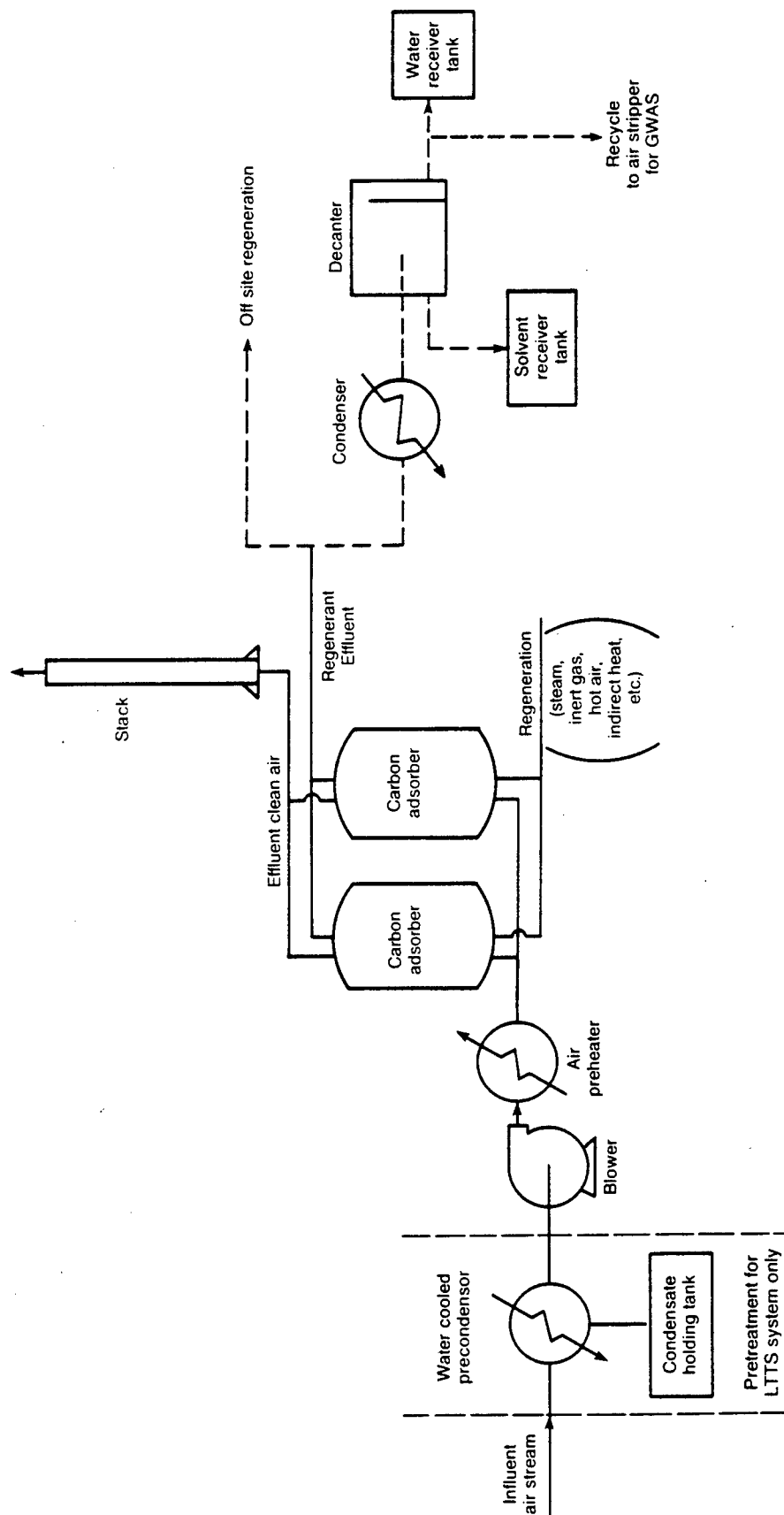
Figure 5. Activated carbon adsorption system schematic diagram.

3.2.3 VOC control efficiency. Control efficiency for activated carbon is typically high for chlorinated solvents at relatively high concentrations. Adsorption capacity drops, according to typical adsorption isotherm data, with lower inlet concentrations. Upon regeneration, some loss of VOC occurs due to the presence of residual noncondensable gases in the carbon bed. As inlet concentrations and, thus, adsorption capacity decrease, these losses become more significant. As a result, some vendors will not recommend activated carbon for very low concentration applications. At anticipated average concentrations for LTTS and ISV, efficiencies are expected to exceed 85 to 90 percent. For GWAS, and as concentrations decline for ISV operation, lower efficiencies may result.

Adsorption capacity and control efficiency are negatively impacted by increasing temperatures and high humidity (>50 percent relative humidity in the air stream). The negative impact of elevated humidity is greater. Therefore, high humidity is addressed in the design and costing for GWAS and ISV applications by heating the inlet air to raise its temperature by approximately 20°F which lowers the relative humidity from 100 percent to approximately 50 percent. For LTTS, the air high temperature inlet stream will be cooled to approximately 70°F, condensing excess humidity, and then reheated to 90°F.

3.2.4 Reliability. The performance of carbon adsorption can be estimated from single solute isotherm data. VOC mixture and moisture effects will typically impact actual performance, in some cases differing by up to 50 percent of projected carbon adsorption capacities.

The fixed multibed carbon system is basic and reliable. Effluent monitoring may be necessary to adjust regeneration frequency as inlet concentrations change. This may be a major concern for LTTS where VOC input rates depend on variable soil concentrations. ISV and GWAS input rates and day-to-day performance are less variable.

3.2.5 Ease of operation/maintenance. The carbon system is readily automated. Its design should make operation and maintenance relatively easy with the exception of LTTS operation with variable inlet concentrations as noted in the previous subsection.

Another concern for adsorption of chlorinated organics in moist air streams is the generation of corrosive dehalogenation products. Corrosion may be a problem for some applications with longer operating life requirements. These concerns may be addressed by specifying appropriate coatings and/or corrosion-resistent materials of construction which are readily available

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from most vendors. A concern associated with carbon treatment of emissions from LTTS is the potential development of hot spots and risk of bed ignition when high concentration slugs of VOC occur. Temperature sensors and safety bypass interlocks may be specified to address this potential problem.

3.2.6 Transportability. Carbon systems of the sizes required here are typically shop-fabricated and skid-mounted. Minimal efforts are necessary for site preparation and pad construction. The major installation efforts would include propane fuel tank, package steam boiler, condensate receivers, utility tie-ins, and support facilities. Portable units are commercially available for single use (no regeneration) applications, and are also feasible for regeneration systems.

Transportable carbon units should be sized with adequate bed cross sectional area to handle the highest anticipated air flows and can be readily designed to operate at one-fifth to one-tenth of the maximum flow rate, if necessary. Regeneration frequencies could be adjusted for use at other sites to account for changes in organic constituents and inlet concentrations as long as the adsorption capacity is sufficient to achieve adequate adsorption cycle length and adequate overall control efficiencies.

3.2.7 Environmental issues. Carbon adsorption is a widely accepted air emission control technology. Residues requiring treatment or disposal include the recovered solvent and condensed water from the regeneration cycle. The solvent would be considered a hazardous waste requiring treatment/disposal. The aqueous condensate would contain chlorinated hydrocarbons at concentrations up to their solubility limits in water. For GWAS, the aqueous condensate would be recycled to the air stripper where the VOC will be stripped and recaptured. For ISV and LTTS, this stream is collected and transported to an off-site treatment/disposal facility.

3.2.8 Proprietary status. This technology is in the public domain. There are no known restrictions on its study or implementation.

3.2.9 Development time. This technology is commercially available and requires no development. For use at low concentrations, some applications testing may be desirable.

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3.2.10 Estimated treatment costs. Treatment costs for equipment, installation, and operation are summarized in Table 6. Additional details are provided in Appendix A.

Operating costs assume part-time operator attention since the system would operate and regenerate automatically. Interlocks would shut down the primary IR treatment process in the event of a system malfunction. If variable soil characteristics present a problem for LTTS operation, labor, and monitoring costs would increase. Operating costs are also sensitive to increases in off-site treatment/disposal cost.

3.3 Fume incineration

3.3.1 Process description. Fume incineration is an established commercial technology used for VOC emission control. Energy is provided by fuel combustion to raise emission stream temperature. Excess air is provided, if necessary, to promote oxidation of VOC's. Most organic compounds can be effectively oxidized to form CO_2, H_2O, and other typical combustion by-products. The temperature and residence time required for effective destruction depends on the properties of the organic compounds encountered. Chlorinated hydrocarbons typically require higher temperatures and longer residence times for complete combustion. In addition, hydrochloric acid is generated as a combustion product which may require the addition of quench and off-gas scrubbing and limit the capabilities for heat recovery from the effluent gases.

Incineration is typically very efficient and reliable and can achieve virtually complete oxidation of most hydrocarbons. Applying incineration to air emission streams containing low concentrations of VOC's can result in high treatment costs, since the entire air stream must be raised to combustion temperature.

Heat recovery is an important factor in improving the cost effectiveness of fume incineration. Options for heat recovery include an air preheater for the inlet stream, steam generation for use elsewhere at the facility, and heat recovery by sequential use of a high heat capacity solid matrix, a proprietary process of Regenerative Equipment Company, Inc. (REECO). If steam generation capacity can be effectively used on-site, it can significantly improve process economics, particularly if old, inefficient boilers are being replaced. For the LTTS process, steam generated from the afterburner off-gas could be returned directly to the process by using steam as a heat transfer medium in the thermal processor. Optimization of the LTTS/fume incineration process, including heat recovery, is being investigated under another USATHAMA task order.

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TABLE 6. SUMMARY OF ESTIMATED CAPITAL AND OPERATING
COSTS FOR CARBON ADSORPTION/STEAM REGENERATION

	Capital Cost	Annual Operating Cost
In situ volatilization		
Site D	$270,000	$ 80,000*
Site G	372,000	177,000
Low temperature thermal stripping	236,000	112,000
Groundwater air stripping	135,000	49,000

*Operating cost presented is for expected 10-month duration of
 operation at Site D or 10/12 of the annual cost.

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For the four application sites, fume incineration could be applied alone or with optional heat recovery (air preheater) and off-gas control of HCl emissions.

3.3.2 Conceptual design. A general schematic of a fume incinerator is given in Figure 6. The heat exchanger, quencher, and wet scrubber units are included as optional equipment. At the average inlet VOC concentrations the HCl emissions of the air streams were estimated as follows:

(a)   ISV Site D -   3.93 pound per hour
       ISV Site G - 11.56 pound per hour
(b)   LTTS   -   5.42 pound per hour
(c)   GWAS   -   0.16 pound per hour

The regulations governing acid emissions vary from state to state and site specific emission modeling should be conducted to determine if HCl emission control would be required. A regulatory emission rate for RCRA hazardous waste incinerators, 40 CFR 264.343(b), limits HCl emissions to 4 pounds per hour. While these VOC emission control systems are typically not considered hazardous waste incinerators, this may be used as an indication of the need for using a wet scrubber. Higher HCL emissions could be permitted for non-RCRA applications if it is demonstrated that no hazard would result. Since this determination could not be made without a site specific assessment, HCL scrubbing was evaluated as an option.

Operating conditions of 1,500°F and a 0.5-second residence time would provide approximately 99 percent destruction of input VOC's, which is adequate in most emission control applications. Higher destruction efficiency can be achieved, if necessary, by increasing temperature and residence time. If, for instance, efficiency equivalent to RCRA hazardous waste incineration requirements were necessary, increasing the temperature to 1,800°F should increase destruction efficiency to 99.99 percent. Fuel usage would increase by 20 to 25 percent, assuming no heat recovery is used. For this analysis, operating conditions which would yield 99 percent efficiency (as high or higher than all other technologies evaluated) were used.

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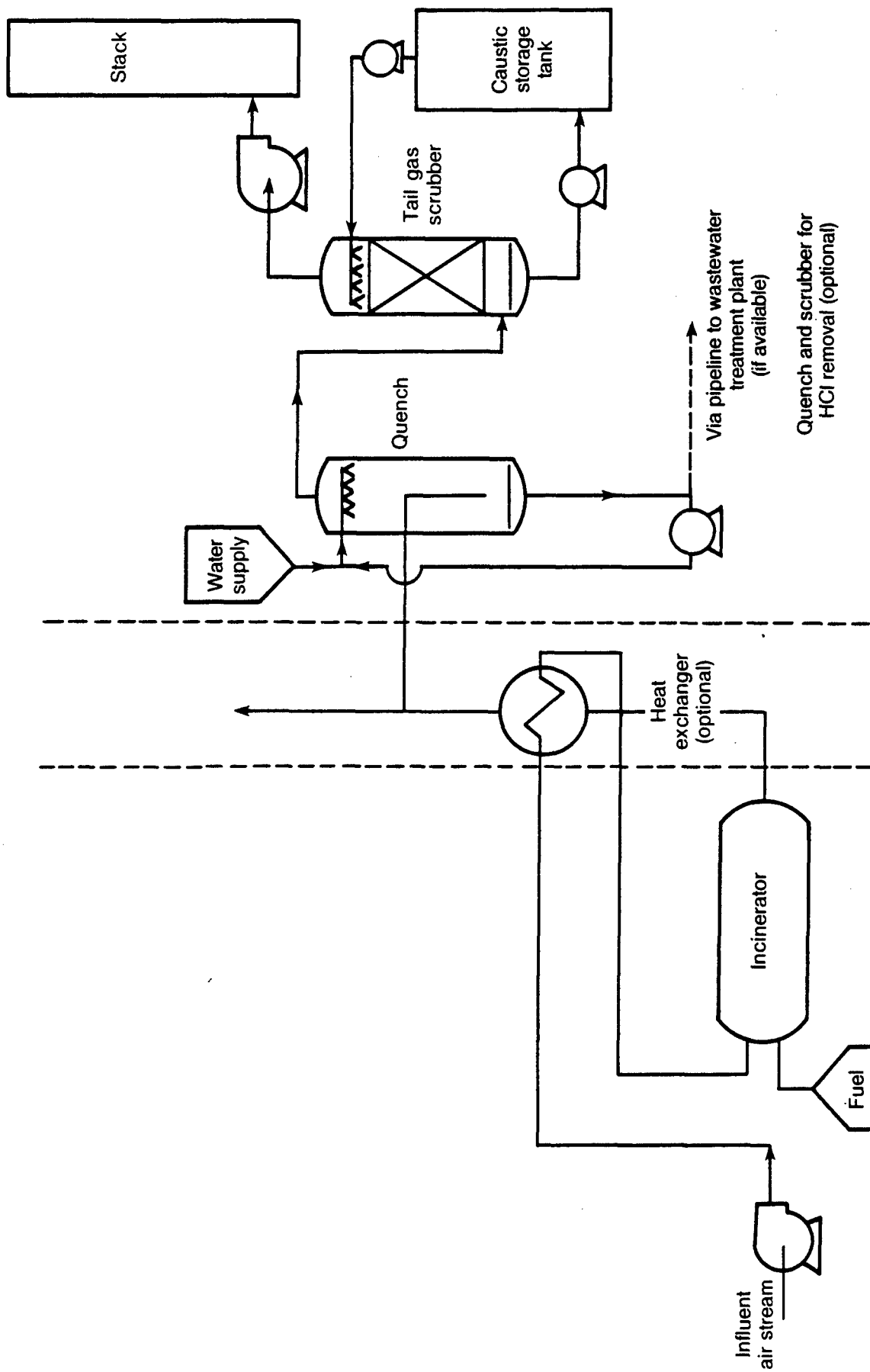
Figure 6.   Fume incinerator schematic diagram.

Where HCl emission control is necessary, the off-gas must be quenched with water to reduce its temperature prior to neutralization. The caustic scrubber would neutralize the HCl in the combustion gases using caustic (NaOH) solution supplied by a caustic storage tank which could be periodically emptied and recharged. The quench water can be supplied by treated groundwater for GWAS. Water supply may present a problem for ISV and LTTS since the sites may be remote and water supply on-site may not be available. With required quench water rates of 1.5 gpm to 5 gpm, significant additional costs (not included in the cost estimates) may be incurred for water supply hookups.

3.3.3 **VOC control efficiency.** Incineration can be designed with the highest control efficiency of any technology identified. Costs were based on a unit capable of 99 percent destruction. Higher or lower efficiencies can be obtained by adjusting operating temperature and residence times. A 99.99 percent destruction is typically achievable by increasing the temperature approximately 300°F from the case evaluated.

3.3.4 **Reliability.** Incineration is one of the most reliable technologies for VOC emission control. Typically, as long as temperature, excess oxygen, and residence time requirements are met, the expected destruction efficiency is achieved. The equipment is reliable and capable of automatic operation with little operator attention. Incinerators can also be designed to operate with a highly variable input load while maintaining high destruction efficiency.

The reliability of a system with heat recovery and HCl scrubbing declines somewhat due to the problems associated with corrosion of equipment. The quench equipment is, in particular, in a harsh environment due to high temperature and the presence of hydrochloric acid. This problem can be adequately addressed by proper selection of equipment, design configuration and use of more exotic materials of construction.

3.3.5 **Ease of operation/maintenance.** Fume incineration typically requires minimal operator attention. Standard safety devices, such as ultraviolet sensors, monitor and, if necessary, shut down the incinerator. Routine maintenance is similar to that for a boiler. The acidic environment may present special corrosion problems for the heat recovery and off-gas scrubbing systems as discussed in the previous subsection.

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3.3.6 Transportability. The basic fume incinerator is typically shop-fabricated and readily transportable. Due to the simplicity of the basic fume incinerator design, a portable unit is feasible. The addition of off-gas caustic scrubbing complicates the process requiring more field assembly. Modular skid-mounted units should still be feasible.

3.3.7 Environmental issues. Incineration is a widely used and accepted technology. The major issue for the application of incineration is the presence of Products of Incomplete Combustion (PIC's) or HCl in the combustion gases. The PIC issue should not be a major technical concern due to the dilute nature of the VOC's in the feed air and proper incinerator design. The acidic off-gases can be controlled though the use of a caustic scrubbing system. As discussed above, HCl emission regulations vary by state and are typically regulated based on the potential for localized acidic deposition, a less quantifiable restriction. While relatively high acid emissions may be permitted, the hazardous waste incineration limitation may increasingly be used as a bench-mark, above which justification may be required. This may increase the difficulty of permitting.

3.3.8 Proprietary status. This technology is in the public domain. There are no known restrictions on its study or implementation.

3.3.9 Development time. Incineration is commercially available and requires no further development for these applications.

3.3.10 Estimated treatment costs. Treatment costs for equipment, installation, and operation are summarized in Table 7. Additional details are provided in Appendix A. Three options are considered:

(a) Incineration.
(b) Incineration with heat recovery.
(c) Incineration with heat recovery, quench, and off-gas caustic scrubber.

Operating costs assume part-time operator attention. Interlocks would shut down the primary IR treatment process in the event of a system malfunction.

Operating costs are very sensitive to energy costs. Propane use was assumed due to the likelihood of a remote location. The availability of low cost natural gas could reduce operating costs.

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TABLE 7. SUMMARY OF ESTIMATED CAPITAL AND OPERATING
COSTS FOR FUME INCINERATION

	Capital Cost[a]	Annual Operating Cost
In situ volatilization		
Site D		
Option A[b]	$ 136,000	$274,000[e]
Option B[c]	597,000	116,000[e]
Option C[d]	766,000	175,000[e]
Site G		
Option A	193,000	585,000
Option B	755,000	247,000
Option C	1,021,000	340,000
Low temperature thermal stripping		
Option A	150,000	156,000
Option B	601,000	94,000
Option C	775,000	165,000
Groundwater air stripping		
Option A	113,000	95,000
Option B	451,000	70,000
Option C	585,000	114,000

Notes:

[a]Major equipment costs include installation, engineering, and contingency.
[b]Option A includes an incinerator with no scrubber or heat recovery.
[c]Option B includes incinerator and heat exchanger at 75 percent heat recovery.
[d]Option C includes incinerator, heat exchanger, quench, and caustic scrubber.
[e]Operating cost is for the expected 10-month duration of operation at Site D or 10/12 of the annual cost.

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3.4 PURASIV carbon bead system.

3.4.1 Process description. The PURASIV process, which was marketed by Union Carbide, uses a fluidized bed of carbon beads. This system is used commercially in industrial applications for the recovery of volatile solvents from an air stream. The solvent laden air is introduced into the bottom of the adsorber section and travels upward countercurrent to the fluidized carbon beads which move downward through a series of perforated trays. The carbon beads move downward from tray-to-tray via a weir/downcomer. When it leaves the bottom tray of the adsorber section, the carbon is no longer fluidized. It flows as a dense bed through the desorption section of the column. The carbon passes through the tube side of a shell-and-tube heat exchanger, where it is indirectly heated to the desorption temperature. Desorbed solvent is purged from the carbon by the introduction of direct-contact nitrogen gas. This stripping gas carries the solvent to the condenser and separator.

The condensed solvent is typically reused in previous commercial installations but can be collected for off-site treatment/disposal. The stripping gas exiting the condensor is typically recycled to the desorption heat exchanger resulting in no emission losses in the regeneration cycle (as would occur with conventional activated carbon).

The indirect heating used in the regeneration section results in purge gas VOC concentrations 50 to 100 times that of the inlet air stream. Nitrogen is used in nonchlorinated solvent applications to prevent explosive conditions. The useful operating capacity between adsorption and desorption cycles is typically 5 to 10 percent. With lower concentrations present in the subject emission sources, capacities are expected to drop to the 1 to 2 percent range.

Due to the complexity of this process, all previous applications have been for high air flows (20,000 to 90,000 cfm) and high concentrations of water-soluble solvents. The inert gas regeneration allows soluble solvent recovery with a minimum of water mixed with the solvent. Due to low interest in the process, Union Carbide no longer offers it, but it remains available from its Japanese licensor, Kureja.

3.4.2 Conceptual design. A process schematic of the PURASIV system is given in Figure 7. In the four IR applications, the condensed VOC (mixed chlorinated solvents) cannot be reused on-site, so they would be disposed of off-site at a commercial incineration facility.

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Activated
carbon
reservoir

Purified
air

Fluidized bed
carbon beads

Influent
air stream

Nitrogen

Solvent
laden
carbon

Nitrogen

N₂/solvent mix

Shell-in-tube
heat exchanger

Condenser

Regenerated
carbon
beads

Separator

Solvent

Air lift
blower
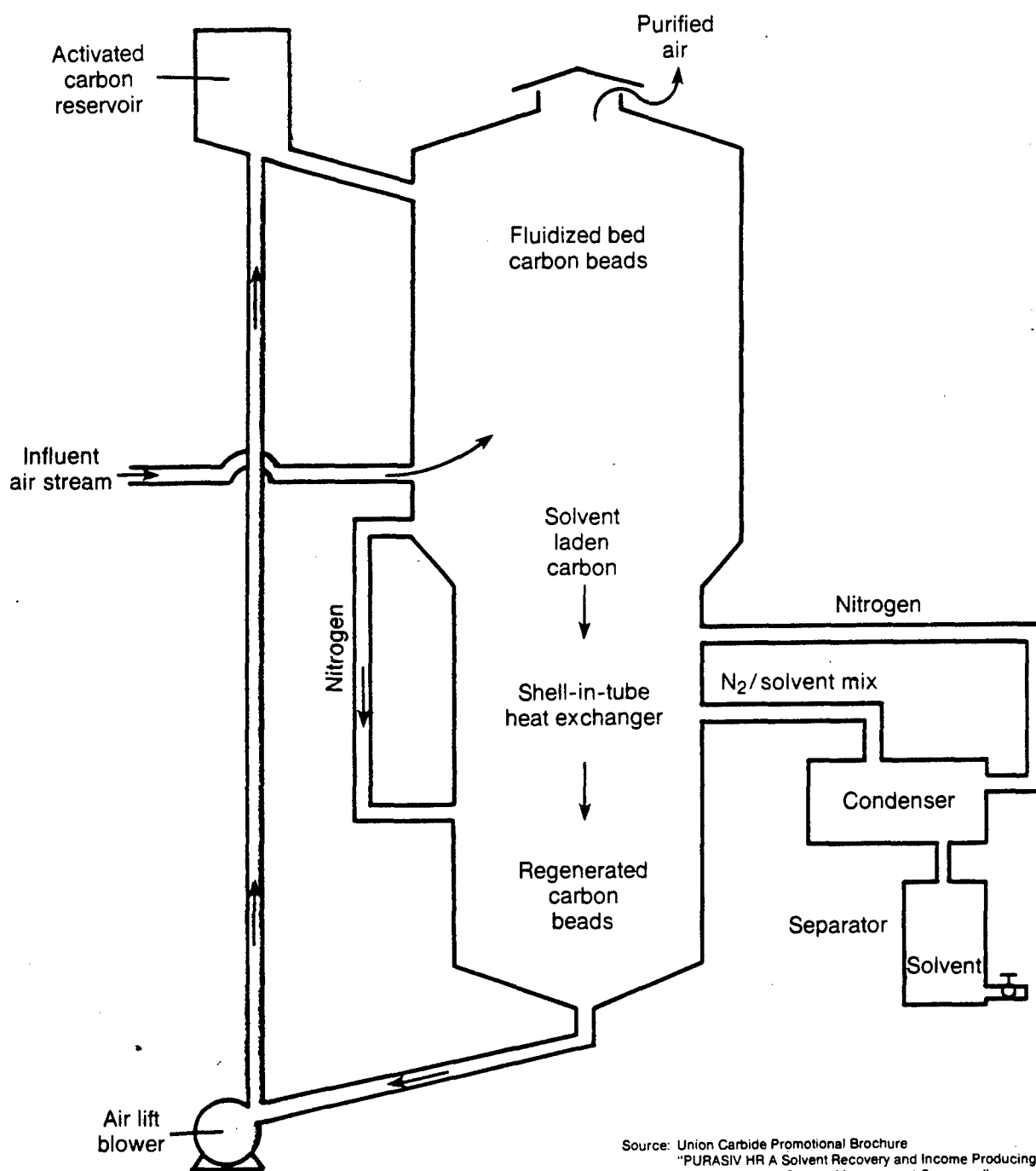
Figure 7. PURASIV schematic diagram.

An alternative design concept was considered which would destroy the VOC's on-site. The PURASIV unit can be readily combined with fume incineration to destroy concentrated VOC's more efficiently. Since the chlorinated organics do not present an explosion hazard, air could be used as the purge gas in the PURASIV unit. This purge gas stream could then be fed to a fume incinerator with minimal additional combustion air. Based on a 50 to 100 fold concentration of organics in the purge air, energy consumption and associated operating costs for incineration would decrease.

The main disadvantage of this mode of operation for these low flow rate applications is the complexity and high capital cost of the base PURASIV process. In addition, a combined PURASIV/ fume incineration system was never explored by Union Carbide. Since the smallest PURASIV unit considered feasible to date (but not necessarily cost-effective) would process approximately 10,000 cfm, the PURASIV/incineration alternative was not evaluated in this study. For cost-estimating purposes, solvent recovery using the standard PURASIV process with off-site solvent incineration was utilized.

Several factors make the application of this process to LTTS, ISV, and GWAS questionable. Extensive design engineering would be necessary to down size the PURASIV process. In addition, small-scale applications may be cost prohibitive. For the purposes of comparison, however, costs were developed based on extrapolation from Union Carbide's experience with larger size units.

3.4.3 VOC control efficiency. Since regeneration gases are recycled to the process, the PURASIV system is expected to have control efficiencies equal to or higher than the conventional carbon adsorption/desorption system (i.e., greater than 90 percent). However, commercial units were designed for and operated on air streams which had a much higher concentration of VOC's, typically in the percentage concentration range. There is very little operational experience in treating the low levels of VOC's expected in the application of remedial technologies investigated in this study.

3.4.4 Reliability. The PURASIV system is a complex process. While the system should provide consistent control efficiencies when operating properly, the equipment reliability is likely to be lower than for conventional carbon systems.

3.4.5 Ease of operation/maintenance. It is expected that the PURASIV system will require a high level of operator attention. Operators will likely require more extensive training for this application. Specialized maintenance may also be necessary.

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3.4.6 Transportability. Due to the complex nature of this equipment it is unlikely that an easily transportable unit could be constructed. Units could be designed to be reusable but extensive assembly/disassembly on-site is likely.

3.4.7 Environmental issues. The PURASIV process is a specialized carbon adsorption process. As carbon adsorption is a widely accepted form of VOC emission treatment, it is expected that permitting should be routine, with stack testing upon startup a likely requirement. Condensed VOC's would be considered a hazardous waste requiring treatment/disposal.

3.4.8 Proprietary status. This is a proprietary technology and has been marketed in the United States by Union Carbide under a licensing agreement with the Japanese firm, Kureja, which developed the process. However, Union Carbide has recently decided to withdraw from marketing this technology and no longer offers the PURASIV system. Further work in this area would require the cooperation of the original development firm through its U.S. representative, Craeha Corporation of America.

3.4.9 Development time. All of the commercial units developed by Union Carbide are too large for the applications in this study. A system sized for the appropriate concentrations and flow rates would require extensive design engineering effort. It is expected that the time required for developing a licensing agreement, design, fabrication, and installation of a "down-sized" unit would be up to 3 years.

3.4.10 Estimated treatment costs. Expected VOC emissions from the four site applicaitons are outside the range of chemical compounds, flows, and concentrations where PURASIV has been commercially applied. Order-of-magnitude costs were developed for comparison with conventional technologies. Costs for a system designed to process 10,000 cfm were obtained, based only on the past experience of Union Carbide as conveyed in telephone communications. (7) These costs are summarized in Table 8. Additional details are provided in Appendix A.

Further reductions in processing capacity would require extensive expenditures for engineering design. Reductions in capital cost would be limited due to process complexity. It is estimated that the PURASIV system would have a minimum installed cost (exclusive of engineering design) of $600,000 to $750,000 for the smallest feasible sizing. These estimates assume a installation factor of 2.0 to 2.5 times equipment cost based on a grass-roots installation.

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TABLE 8.   SUMMARY OF ESTIMATED[a] CAPITAL AND OPERATING COSTS
FOR PURASIV PROCESS - GENERIC APPLICATION AT 10,000 CFM

Capital Cost	Annual Operating Cost
$1,000,000 to 1,250,000	$300,000 to 400,000

[a]Costs are gross estimates based only on past operating
experience as conveyed by telephone communication with Union
Carbide. An installation factor of 2.0 to 2.5 was applied to
estimated equipment cost.

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3.5 KPR Carbon Fiber/Incineration System

3.5.1 Process description. A variation on carbon adsorption technology is the KPR system in which a carbon fiber is used. This fiber is reported to have improved temperature swing adsorption and desorption properties relative to granular activated carbon (i.e., greater temperature effects on adsorption capacity). The KPR system was developed in Japan and is being marketed in the United States by Met-Pro Corporation.

The KPR carbon fiber system was designed to be operated in a continuous process where VOC's are collected in one zone and undergo hot air desorption in another. The regenerant hot air stream contains 5 to 15 times the VOC's of the influent air. This desorbed gas stream is then treated by conventional destruction or recovery systems. Destruction systems can operate more cost effectively due to the higher VOC concentration and reduced total air flow rate.

The KPR fiber carbon system has been marketed as a tandem carbon adsorption/desorption and incineration process. By concentrating the dilute VOC air streams using the KPR unit, the size of the fume incinerator can be reduced along with lower fuel costs for operating the incinerator.

The concentration of VOC's in the desorption air stream is limited, however, by the use of air as the heating medium. The use of desorption air is desirable for KPR's intended commercial market of flammable paint solvent applications where organics concentrations must remain below the Lower Explosive Limit (LEL) due to safety considerations. For chlorinated hydrocarbons and lower VOC concentrations where the LEL would not be exceeded, further concentration could potentially be achieved by modifying the process to use indirect heating in the regeneration step. This option is not presently available, however, so the KPR/Incineration process offered by Met-Pro was used as the basis for the evaluation.

3.5.2 Conceptual design. A cross section schematic of a KPR unit is shown in Figure 8 along with a more-detailed schematic of the KPR cylinder-type rotor. The wedge section of the cylinder rotor is in the desorption mode while the rest of the cylinder rotor is in the adsorption mode. A schematic for the combined KPR/Incineration system is presented in Figure 9.

Met-Pro indicated that the KPR system was not well suited to these low flow applications and was hesitant to estimate costs for equipment. They did provide costs for generic applications sized at 10,000 and 20,000 cfm. This was used to extrapolate probable costs for the subject applications. Met-Pro does not anticipate building incinerators with off-gas scrubbing, however, so this option was not evaluated. (8)
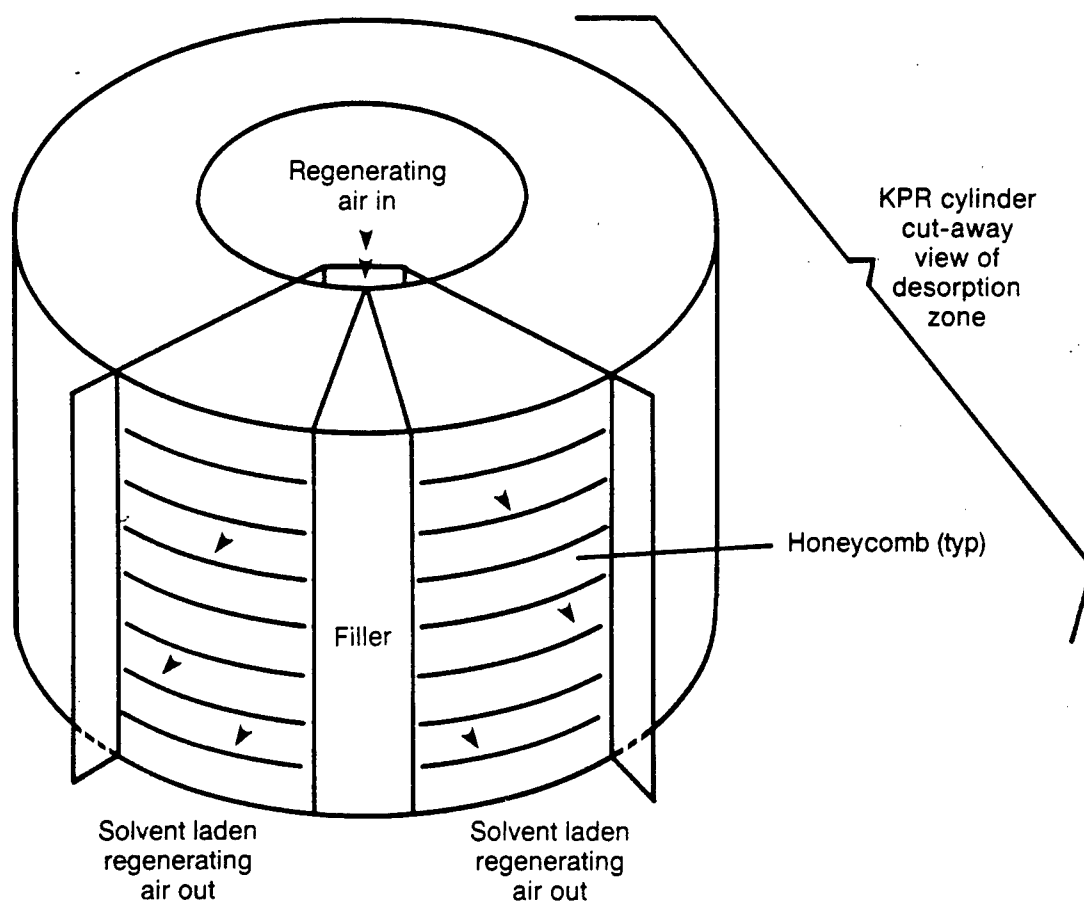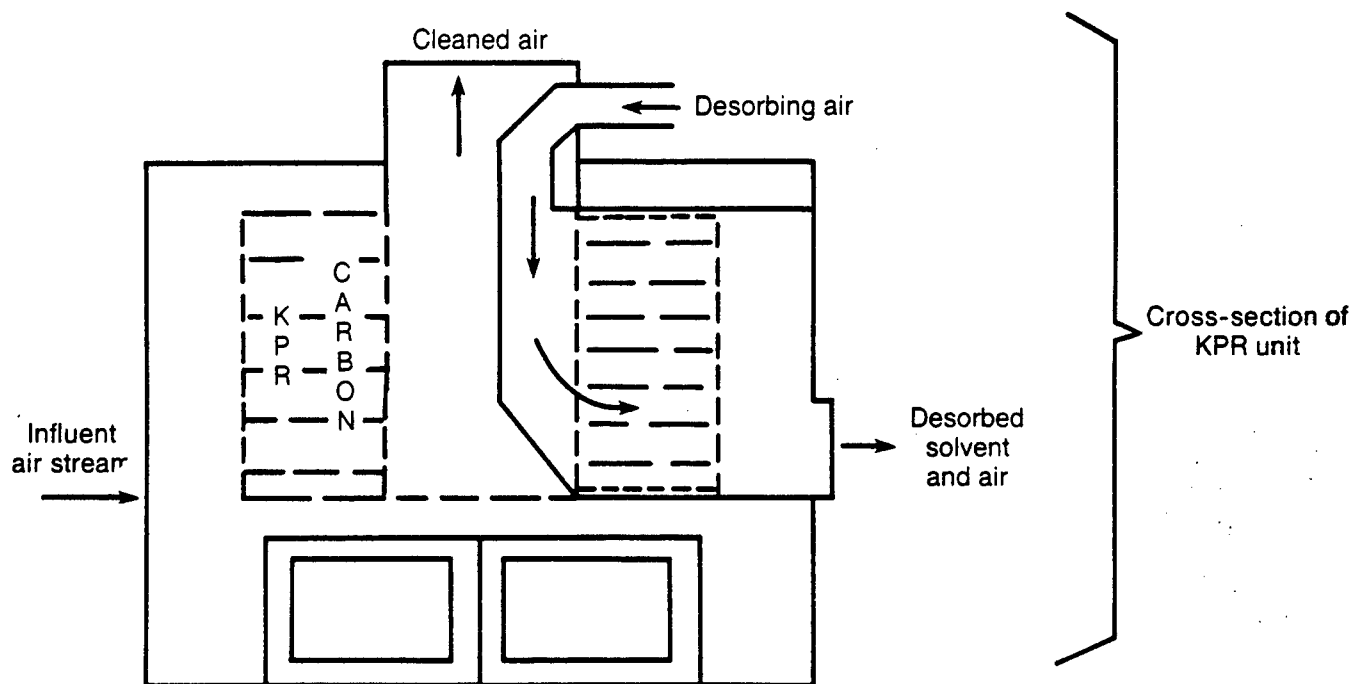
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Figure 8.   KPR carbon fiber adsorption unit schematic diagram.

Cleaned air

Desorbing air

Cross-section of
KPR unit

C
A
R
B
O
N

K
P
R

Influent
air stream

Desorbed
solvent
and air

Regenerating
air in

KPR cylinder
cut-away
view of
desorption
zone

Honeycomb (typ)

Filler

Solvent laden
regenerating
air out

Solvent laden
regenerating
air out
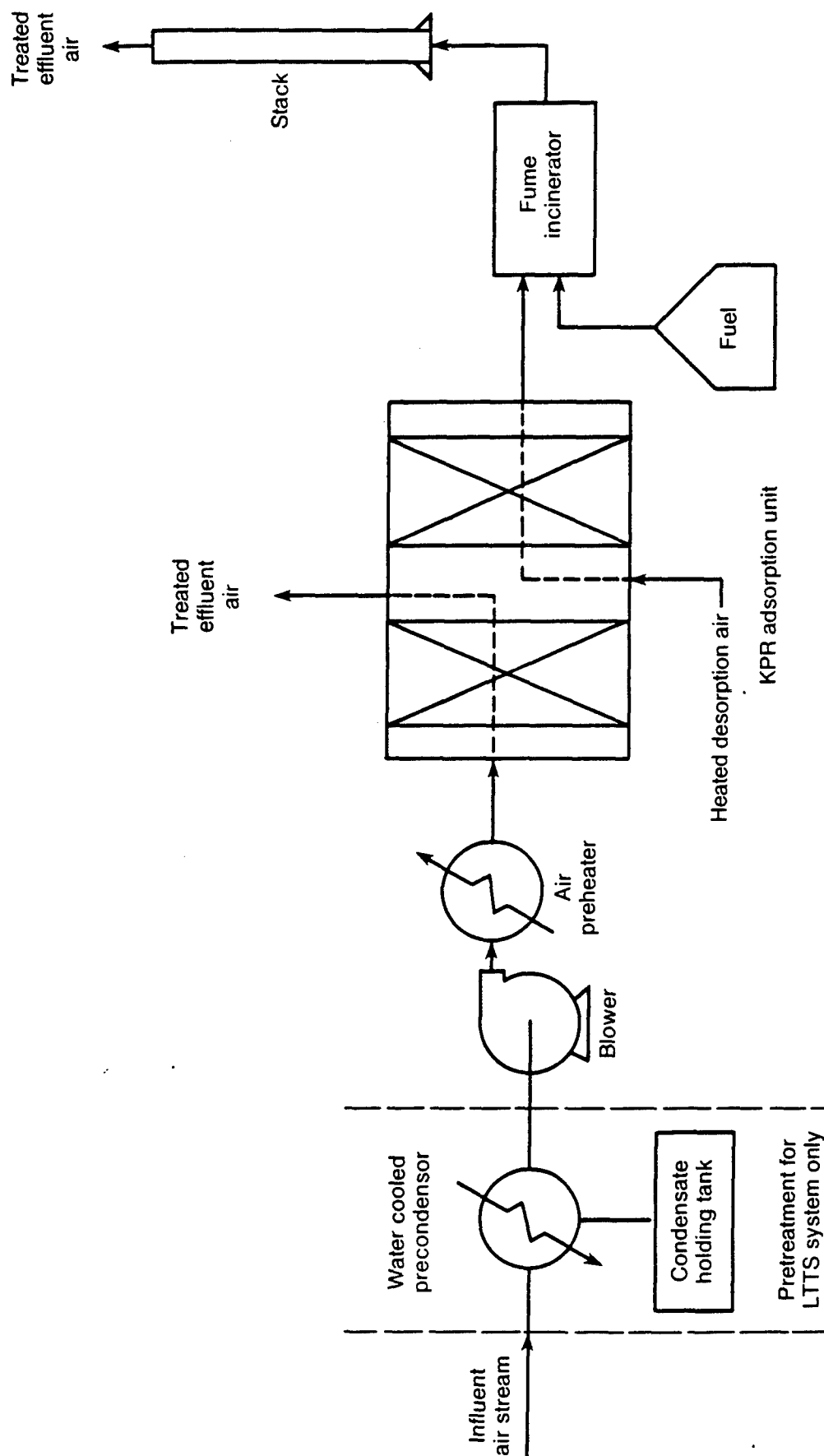
Figure 9. Tandem KPR/fume incineration system schematic diagram.

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The KPR carbon fiber is reported to have improved temperature swing desorption properties as compared with granular activated carbon. Since the KPR process is proprietary, however, design parameters are not available. As a result, independent confirmation of the design and cost data was not possible.

3.5.3 VOC control efficiency. The KPR/incineration system directly incinerates the regeneration off-gases, so control efficiency depends on the efficiency of the primary adsorption stage. Control efficiencies should be equal to or higher than conventional carbon adsorption/desorption systems (i.e., >90 percent). The intended incineration applications for KPR systems are generally higher flow, more concentrated air streams containing nonchlorinated organic compounds. There is little operational experience in treating low levels of chlorinated VOC's. Also, the adsorptive characteristics of the fiber are not publicly available and have not been explored for low concentration contaminants.

3.5.4 Reliability. The KPR system performance could be estimated from single solute isotherm data for the KPR fiber, if they were available. Mixture and moisture effects would impact actual performance, differing in some cases by up to 50 percent of projected single solute adsorption capacity. Monitoring may be useful to adjust regeneration rates (by adjusting KPR carousel rotation speed). As with conventional carbon adsorption, this may be more of a concern with the LTTS than ISV and GWAS systems due to more variable VOC concentrations in the feed air.

3.5.5 Ease of operation/maintenance. The KPR system is automated. The tandem unit operations will require more operator attention than a single unit but its operation and maintenance requirements should be manageable by personnel with average skills and training. The generation of corrosive dehalogenation products as a result of treating chlorinated VOC's in moist air streams may pose significant maintenance problems for an application with longer operational life. These may be addressed by utilizing appropriate coatings and/or corrosion-resistant alloys which are available, but this may result in some increase in capital equipment costs.

Slugs of high VOC concentration in the inlet air may cause hot spots to develop, risking carbon rotor ignition. Temperature sensors and safety bypass interlocks may be specified to address this potential problem.

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3.5.6   Transportability.   The KPR systems generally considered cost-effective are those which handle high air flow rates. These systems are, of course, larger and would require field assembly. Smaller units could be designed and shop-fabricated to require less on-site assembly.

If sized for the highest anticipated flows and lowest anticipated adsorption capacity applications, the system operation could be readily modified to operate in other applications by adjusting rotor speed, regeneration air flows, and incineration operating conditions.

3.5.7   Environmental issues.   The KPR system is a special-ized adaptation of carbon adsorption with a fume incineration system operating in tandem. Given the expected overall system performance, this technology should be acceptable to regulatory agencies. The generation of HCl in the off-gas may require caustic scrubbing as discussed for fume incineration. Since Met-Pro has not applied KPR with HCl scrubbing systems, costs for this option have not been evaluated.

3.5.8   Proprietary status.   This technology is proprietary and marketed in the United States by Met-Pro.

3.5.9   Development time.   KPR systems available through Met-Pro have been used commercially in Japan. No development is required for use with nonchlorinated compounds at high flow rates and concentrations. Additional study would be necessary for applications with low flow rates and low concentrations of chlorinated hydrocarbons.

3.5.10   Estimated treatment costs.   Met-Pro indicated that the KPR system was not cost-effective compared with thermal incineration for the four site applications due to the low air flow rates. (8) The high capital cost of the KPR system would only be offset by the lower operating cost for energy consump-tion if the air flow rates were high and the operating life long enough.

Met-Pro did not provide equipment costs or design param-eters for the subject site applications. To determine where the KPR system may be cost-effectively applied in the future, Met-Pro was asked to provide costs for the KPR system at the lowest flow rates thought to be cost-effective. Met-Pro provided estimates for equipment costs and power and fuel consumption for units sized to handle 10,000 to 20,000 cfm. Costs for optional heat recovery and off-gas scrubbing systems for the fume incinerator were not estimated.

Based on capital cost for two equipment sizings (10,000 and 20,000 cfm), the capital cost for lower air flow applications can be projected. A scale-up factor using an exponential scale-up relationship can be calculated by interpolating between the two points using the following equation:

$$(Cost)_1/(Cost)_2 = [(Capacity)_1/(Capacity)_2]^x$$

Inputing the equipment cost estimates provided by Met-Pro results in a scale-up factor of x ~ 0.17. The low factor indicates that little reduction in cost would be achieved for smaller units (less than 10,000 cfm) due to the complexity of the equipment. Using this factor to extrapolate downward in size to the air flows exhibited in the subject emission streams, approximate costs were developed for the purposes of comparison.

Power is consumed primarily for air movement equipment and is approximately linearly proportional to air flow. Fuel consumption will be impacted by adsorption/desorption characteristics and will, therefore, be influenced by the VOC constituents present and the concentrations. Since Met-Pro did not provide design information, it was assumed that energy costs would be linearly proportional to air flow.

Using the above assumptions, cost estimates for GWAS, ISV, and LTTS VOC emission control are summarized in Table 9. Additional details are provided in Appendix A. These estimates should only be considered rough approximations since they are not based on source-specific design characteristics other than air flow, and the construction of these smaller units would have to include extra cost (not estimated) for substantial engineering design efforts.

3.6   Fluidized bed catalytic oxidation.

3.6.1   Process description.   Catalytic oxidation is a commercially-available technology which utilizes catalysts to lower the activation energy and temperatures required to fully thermally oxidize organic compounds. A catalyst typically lowers oxidation temperature requirements to between 500° and 900°F, depending on the constituents, and also lowers the retention time requirements necessary to achieve required performance. Where contaminant concentration and heat values are high enough, catalyst operation with a heat exchanger requires little or no fuel except for unit start up.

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TABLE 9. SUMMARY OF ESTIMATED[a] CAPITAL AND
OPERATING COSTS FOR KPR/INCINERATION

	Capital Cost[b]	Annual Operating Cost
In situ volatilization		
Site D	$775,000	$120,000[c]
Site G	885,000	190,000
Low temperature thermal stripping	715,000	129,000
Groundwater air stripping	615,000	127,000

[a]Based on extrapolation to lower equipment sizing using 0.17
exponential scale-up factor.
[b]Installation factor of 2.5 was used due to grass-roots
installation at a remote location.
[c]Operating cost is for the expected 10-month duration of
operation at Site D or 10/12 of the annual cost.

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The role of the catalyst is to decrease the reaction activation energy, thus allowing the reaction to proceed at a lower energy level (and, thus, lower temperature). Oxidation is accomplished by diffusion of the contaminant gases from the bulk phase to the catalyst surface where chemisorption of the organic material to the active site occurs. At this point, the oxidation reaction proceeds at an energy level dependent upon the orientation of the reactant in relation to the active site, and the type and strength of molecular bonds. After oxidation is complete, the products are desorbed from the catalyst surface and diffused into the bulk exhaust stream flow. The temperature required for conversion is dependent upon the contaminant concentration and the type and amount of catalyst required for the application.

Typically, catalysts are composed of a noble metal coated on activated alumina. They are effective and can significantly lower operating costs as compared with fume incineration. These catalysts, however, are susceptible to poisoning by halogens. Two methods for combatting the fouling of catalysts have been developed. The first is to utilize a fluidized bed catalytic reactor, which removes surface fouling by abrasive action. This is effective for a nonporous catalyst matrix where fouling is a surface phenomenon. The abrasive action requires a catalyst resistant to abrasion. The second approach is the development of catalysts which are not fouled by the products of halogenated hydrocarbon oxidation. These two approaches have reportedly been combined in a proprietary commercial process developed by ARI International.

3.6.2 <u>Conceptual design</u>. The fluidized bed design is relatively simple. The catalyst beads rest on support matrix. The bed is expanded upon the input of air into the oxidation (unit incinerator) resulting in gentle abrasive contact which scours the catalyst surface. The bed does not "circulate" as in catalyst cracking fluidized beds, so no complex catalyst transport loops are required. A schematic for the ARI fluidized bed catalytic unit is shown in Figure 10.

Like thermal incineration, this process could be designed with heat recovery from the off-gases as long as outlet temperature remains above the dew point due to the potential for HCl corrosion problems. Off-gases may be quenched to lower the temperature and scrubbed to remove HCl. The overall process configuration including optional heat recovery and off-gas scrubbing is similar to that presented in Figure 6 for fume incineration.

3.6.3 VOC control efficiency. Catalytic oxidation control efficiencies typically approach those available by high temperature thermal incineration.

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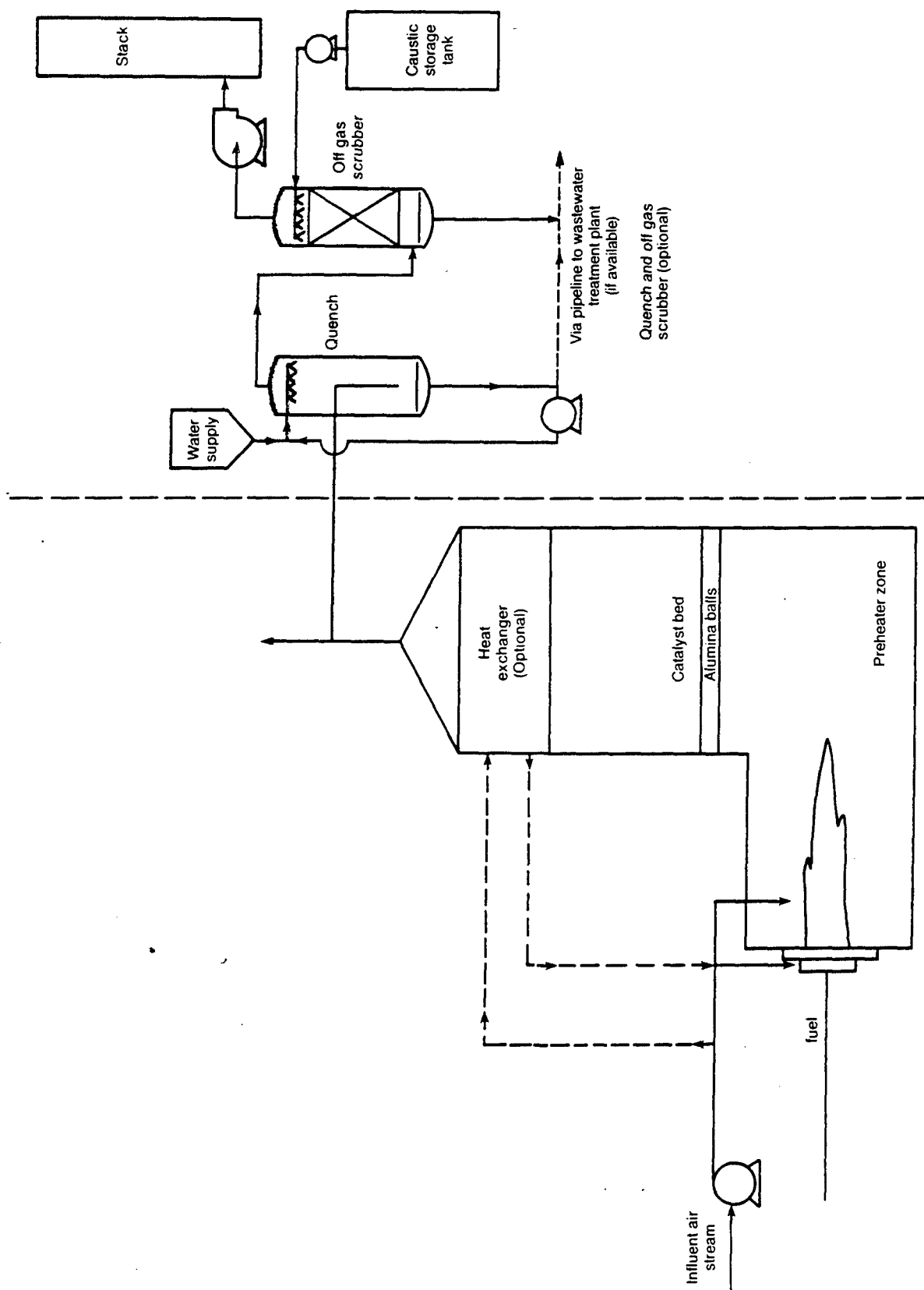
Figure 10. ARI catalytic oxidation schematic.

A test program of ARI's pilot system was conducted by Radian Corporation for the EPA and the U.S. Air Force. (9) The tests were conducted under a variety of temperature and residence times. The test vapors consisted of a mixture of chlorinated hydrocarbons including vinyl chloride, dichloroethylene, trichloroethylene, and tetrachloroethylene at low concentrations (3 to 200 ppmv). Three of the test streams were representative of emissions from air strippers used to treat contaminated groundwater at U.S. Air Force bases. The results showed that the fluidized bed catalytic incinerator was capable of achieving overall destruction efficiencies of greater than 98 percent. Costs were based on a unit capable of 99 percent overall VOC destruction.

3.6.4 Reliability. Like conventional fume incineration, catalytic oxidation is a highly reliable process where efficiencies will remain high as long as adequate residence time and temperature are maintained. The fluidized bed is not expected to increase operator attention significantly since the bed fluidized by the gas flow does not circulate, but remains in place above the support grid. The process equipment has been applied in numerous commercial applications at higher concentrations and is thought to be reliable. The catalytic incinerator may require periodic replacement of spent catalyst, with an expected catalyst life-time of two years. The system can readily respond to a variable input load while maintaining efficiency by adjusting fuel input to maintain adequate temperature.

Similar to the conventional fume incinerator, overall equipment complexity increases and reliability declines with the addition of heat recovery and caustic scrubbing to the process system. The potential for corrosion in the off-gas systems would require corrosion-resistant construction materials.

3.6.5 Ease of operation/maintenance. Catalytic oxidation units typically require minimal operator attention. Standard safety devices, such as ultraviolet sensors, monitor and, if required, shut down the unit. The acidic environment may present special corrosion problems for the heat recovery and off-gas scrubbing systems.

3.6.6 Transportability. The catalytic oxidation unit is shop-fabricated and can be skid-mounted. Units are presently available which are readily transportable. The addition of a heat exchanger and off-gas scrubbing complicates the system and requires more field assembly and disassembly, but skid-mounted modular units could be fabricated.

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The ability to turn down air flow rates to adjust to different sites is bounded only by the range where adequate fluidization occurs. The unit should be sized to treat the maximum air flow and achieve the highest temperature necessary for the anticipated applications.

3.6.7   Environmental issues.   Catalytic oxidation should differ only marginally from fume incinerators in this area. The major issue for the application of this technology is the emission of HCl in the off-gases. The application of caustic scrubbing could be required, resulting in an increase in the cost and complexity of treatment.

3.6.8   Proprietary status.   Catalytic oxidation itself is not a proprietary technology. However, the specific catalyst for the destruction of chlorinated VOC's in a fluidized bed has been patented by ARI International of Palatine, Illinois. This is reported to be the only thermal catalytic process marketed which is resistant to poisoning by the combustion products of halogenated hydrocarbons. The U.S. Air Force is reportedly continuing its investigation of catalytic oxidation with a catalyst development program designed to further optimize catalyst design for the low concentration chlorinated organic applications. (10)

3.6.9   Development   time.   Catalytic   incineration   is commercially available through ARI. Several units are treating chlorinated hydrocarbons at industrial sites. The application of this technology is possible with little further development. Development work might include a demonstration test for a low concentration chlorinated hydrocarbon emission source.

3.6.10   Estimated treatment costs.   Treatment costs for equipment   and   installation   are   summarized   in   Table   10. Additional details are provided in Appendix A. Three treatment configurations are considered:

(a)   Catalytic oxidation.
(b)   Catalytic oxidation with heat recovery.
(b)   Catalytic oxidation with heat recovery, quench, and off-gas scrubbing.

Operating costs were based on part-time operator attention since interlocks would shut down the primary IR process in the event of system malfunction.

Operating costs are very sensitive to energy costs. The use of propane for fuel was assumed due to the likelihood of a remote location. The availability of low cost natural gas at the site could reduce operating costs.

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TABLE 10. SUMMARY OF ESTIMATED CAPITAL AND OPERATING
COSTS FOR FLUIDIZED BED CATALYTIC OXIDATION

	Capital Cost[a]			Annual Operating Cost		
	A[b]	B[c]	C[d]	A	B	C
In situ volatilization						
Site D	$178,000	$263,000	$ 913,000	$193,000	$135,000	$235,000[e]
Site G	255,000	380,000	1,340,000	394,000	257,000	392,000
Low temperature thermal stripping	150,000	214,000	714,000	77,000	65,000	156,000
Groundwater air stripping	113,000	163,000	565,000	67,000	57,000	117,000

[a]Major equipment costs include installation, engineering, and contingency.
[b]Option A includes an incinerator with no scrubber or heat recovery.
[c]Option B includes incinerator and heat exchanger at 42 percent heat recovery.
[d]Option C includes incinerator, heat exchanger, quench, and caustic scrubber.
[e]Operating costs for the expected 10-month duration of operation at Site D is approximately 10/12 of the annual cost shown (as detailed in Appendix A).

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3.7 UV/ozone/catalytic oxidation

3.7.1 Process description. UV/ozone/catalytic oxidation is a new process which is under development for application to destruction of VOC's in air streams. The process, developed by Ultrox International, has evolved from UV/ozone treatment for destruction of VOC's in water streams. UV/ozone treatment of VOC's in water typically results in significant volatilization of VOC's, resulting in air emissions. Commercialization is anticipated within approximately two years.

This process involves mixing the inlet VOC laden air with small quantities of ozone, preheating the air to a moderate temperature (approximately 100°F), and passing the mixture over a proprietary catalyst which is irradiated with UV light. In some cases, oxidation can occur either without ozone or without UV light. Preliminary testing, conducted by Radian Corporation for the U.S. EPA and U.S. Air Force, was published in September 1986. (9,10) These tests showed that with ozone addition dichloroethylene and trichloroethylene can be almost completely removed from an air stream. The process apparently does not completely oxidize these compounds, however, and produces methyl formate and methyl acetate as byproducts in the effluent from the process. Without ozone, no byproduct formation was found but destruction efficiencies dropped to below 70 percent. Preliminary cost estimates by Ultrox, International indicate that the technology may be competitive with current state-of-the-art technology for VOC emission control.(11) Further study is indicated, however, to determine the following:

(a) Performance and anticipated cost at various influent VOC concentrations.
(b) Performance with different organic compounds.
(c) Rate and type of byproduct formation.
(d) Regulatory requirements governing emissions of these byproducts.

3.7.2 Conceptual design. The equipment pilot tested by Radian .Corporation was designed to treat both contaminated water with UV/ ozonation and the off-gases from water treatment with UV/ozone/catalytic oxidation. A process schematic for the overall water/air treatment process is presented in Figure 11.

For application to the streams outlined in this study only the vapor phase UV/ozone/catalytic reactor would be utilized. The major equipment components include the ozone generation unit and the UV/catalytic reactor.

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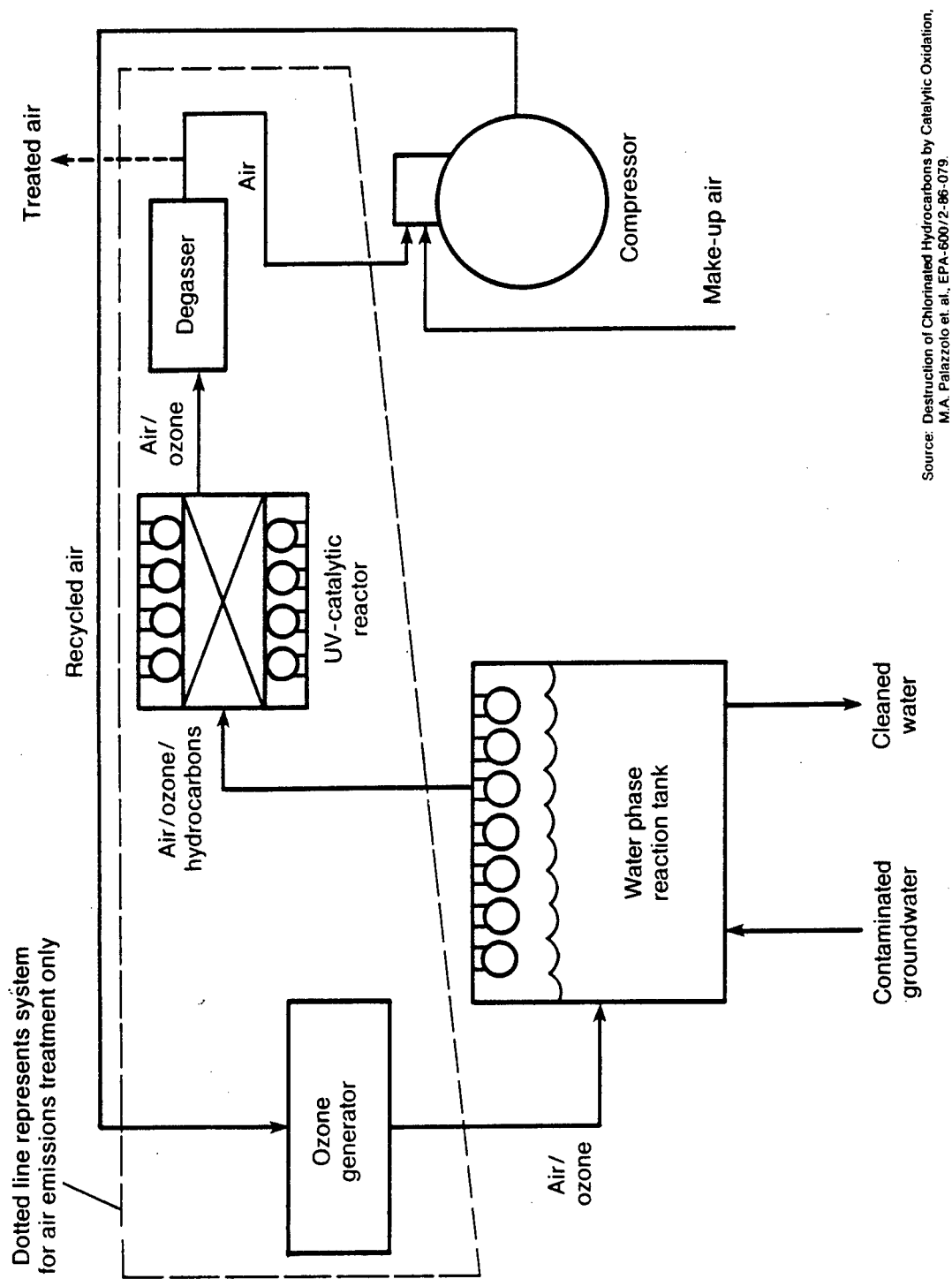
Figure 11. Pilot UV/ozone/catalytic test system schematic diagram (for water/air treatment).

Source: Destruction of Chlorinated Hydrocarbons by Catalytic Oxidation, M.A. Palazzolo et. al., EPA-600/2-86-079.

Design parameters are not presently available for the compounds of interest. The major cost and sizing considerations include VOC constitutents, concentrations, temperature, and flow rate. Residence time, ozone capacity, UV capacity, catalyst mass, and temperature must be adjusted to the requirements of the VOC constituents present. Since the process is not yet commercial, system cost estimates were based on the best estimates of Ultrox International for equipment. (11) Independent confirmation of the equipment cost data provided was not possible.

3.7.3 VOC control efficiency. Testing presented in the above referenced EPA/U.S. Air Force report indicated that dichloroethylene and trichloroethylene can be almost completely removed with the addition of ozone, but byproduct formation occurs. Without ozone addition, no byproduct formation occurs but destruction efficiency drops to 70 percent. No data is presently available for other chlorinated organic compounds. The formation of byproducts in the process effluent is a significant concern. The ability of this technology to achieve high performance for a wide range of compounds in a mixed emission source is presently uncertain. Given the early stage of development, performance in these initial tests appear to be promising. With further experimentation, design and operating modifications might be made to improve destruction·efficiencies and reduce byproduct generation.

3.7.4 Reliability. The reliability of process performance has not been demonstrated in laboratory or pilot testing. Potential concerns include moisture effects, life of the catalyst, and the effects of HCl generation. The ozone generation unit and UV light source are relatively reliable components shared with the Ultrox water phase treatment process which has reportedly been used in four commercial applications to date. Variable feed concentrations would require adjustment of the ozone feed rate. It is reported that ozone levels can be controlled based on an outlet ozone level detector to maintain the required excess ozone concentration. (11)

3.7.5 Ease of operation/maintenance. The system is reported to be readily operable. The process can utilize all electric powered equipment (ozone generation, UV lights source, and air preheater) to further simplify operation. Performance should be monitored and can be adjusted by regulating the rate of ozone input. Maintenance may include cleaning of the UV lights and periodic catalyst replacement (estimated at once each year). Other maintenance items are not yet well defined by Ultrox.

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3.7.6 Transportability. The construction of the process equipment would be modular, using components which are similar to the water phase UV/ozonation unit. It is estimated that a skid-mounted unit sized to treat 2,500 cfm would measure approximately 7-feet by 16-feet by 8-feet high. For a unit without HCl off-gas scrubbing, only electrical hookup would be required to provide power. This process could not only be transportable but would readily lend itself to a fully portable operation for short-term use at many sites.

3.7.7 Environmental issues. Environmental issues include the uncertainty that the UV/ozone/catalytic oxidation process can achieve adequate, reliable emission control, and the potential formation of undesirable byproducts. Similar to other oxidation process (i.e., incineration), this process will result in HCl generation and emissions. As discussed for incineration, the HCl emissions could be handled by a caustic scrubber or permitted without scrubbing depending on site specific conditions. Off-site treatment/disposal could be required for blowdown from a scrubber.

3.7.8 Proprietary status. This is a proprietary technology which is being developed by Ultrox International. Ultrox has applied for a patent on the new air emission control process.

3.7.9 Development time. The process is still under development and several critical performance questions remain to be resolved. Ultrox estimates that development could require up to two years. Given the need to resolve significant problems exhibited in early testing, development time may exceed this estimate.

Ultrox is preparing to conduct further development studies under contract to the U.S. Army Construction Engineering Research Laboratory (CERL). Although information dissemination will be limited, USATHAMA may gain access to these results.

3.7.10 Estimated treatment costs. Ultrox indicated that this technology should be competitive with activated carbon systems. However, since the system is proprietary and in the early stages of commercial development, Ultrox would provide little information on specific equipment costs, sizing, or design parameters for the subject applications. The available performance and operating data is limited to two chlorinated organic compounds at low concentrations.

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To determine the approximate costs for application of this technology, Ultrox was asked to provide estimates for a standard unit based on compounds that have been studied. Capital costs, conveyed by telephone, were estimated based on similar aqueous phase VOC destruction equipment components. Ultrox indicated that the scale-up factor would be determined primarily by the most expensive system component, the ozone generator. (11) Costs provided for this component result in an exponential scale-up factor of x = 0.86 based on the following equation:

$$(Cost)_1/(Cost)_2 = [(Capacity)_1/(Capacity)_2)^x$$

Based on an approximate equipment cost of $100,000 for a 2,500 cfm unit, other size units could be cost estimated. Since the unit is all-electric and of modular construction, installation costs may be relatively low. Installation factors could potentially be as low as 1.5 to 2.0. Since the level of uncertainty of final process requirements is high, a more conservative scale-up factor of 2.5 was applied. If a portable, "plug-in" type unit is developed, this technology could have significant cost advantages over other technologies studied due to lower installation costs.

If off-gas scrubbing is necessary capital and operating costs will rise. Since the oxidizer effluent temperature is low, the added cost of scrubbing will not be as high as for incineration or catalytic oxidation. Costs were not developed for the off-gas scrubbing option because this technology and the ability of Ultrox to estimate the base case equipment and operating costs are not well developed.

The principal components which consume power are air preheating, ozone generation, and the UV light source. Preheating requirements depend on inlet air temperatures. Ozone and UV requirements depend both on VOC concentrations and the reaction rates exhibited by the mixture of VOC's. The relationship of cost-to-concentration has not been provided and performance for most of the compounds present in the subject waste streams have not been investigated. As a result, costs for the generic application are presented as described by Ultrox.

Approximate projected capital and operating costs are summarized in Table 11. Additional details are provided in Appendix A. The major unknown factors which could impact actual costs are the design conditions of residence time, ozone addition, and UV dosages required for specific applications. The costs presented here should be considered order-of-magnitude costs for comparison only.

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TABLE 11. SUMMARY OF ESTIMATED[a] CAPITAL AND OPERATING COSTS FOR UV/OZONE/CATALYTIC OXIDATION BASED ON INLET AIR FLOW: GENERIC APPLICATION

	Capital Cost[b]	Annual Operating Cost
In situ volatilization		
Site D	$325,000	$ 89,000[c]
Site G	648,000	143,000
Low temperature thermal stripping	209,000	79,000
Groundwater air stripping	108,000	47,000

[a]Based on extrapolation from 2,500 cfm, generic application using overall 0.86 exponential scale-up factor assumed equal to ozone generator scale-up factor.
[b]Conservative installation factor of 2.5 utilized even though it is a modular, all-electric unit due to the early level of development.
[c]Operating costs for the expected 10-month duration of operation at Site D is 10/12 of the annual costs shown.

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3.8 Oil/Water Emulsion Absorption

3.8.1 Process description. Vapor/liquid absorption is widely used in the chemical processing industry for solvent recovery as well as emission control. Emission control applications include off-gas scrubbing with water or alkaline solution. Mineral oil scrubbers have been widely used for recovery of chlorinated solvents in chemical process applications and in the food processing industry where higher concentrations in the vapor result in good mass transfer. These approaches are not typically feasible for chlorinated hydrocarbon removal from dilute VOC emission sources.

A new technology utilizing an oil/water emulsion was developed by Nalco Chemical Company for emission scrubbing in paint spray booth applications. The oil/water emulsion would be applied in a single-stage fluid wall scrubber to capture both particulates and vapor emissions. The emulsion provides a low viscosity mixture composed of a high boiling point oil and water. Following scrubbing, the emulsion is broken by adjusting pH. The water phase is processed for solids removal and the oil phase is distilled to recover solvent. The oil and water are then reemulsified and reused for scrubbing. Efficiencies reported for spray booth applications are 65 to 70 percent.

Based on reasonable recovery efficiencies for single-stage spray booth applications, WESTON contacted Nalco to investigate the potential for improving efficiencies by multistage or countercurrent packed tower scrubbers. Nalco indicated that scrubbers had been used in the laboratory development work as a contingency approach if single-stage performance was insufficient. The laboratory development work has been confined primarily to nonchlorinated paint-based solvents for paint overspray applications.

Extensive communications with Nalco and HPD Incorporated, their partners in development and marketing, indicated that there is insufficient data on chlorinated hydrocarbon absorption to develop conceptual design parameters and estimate the cost for the subject applications. In addition, HPD cited numerous technical limitations on the application of oil/water emulsions for dilute chlorinated VOC emission sources. (12,13) These include:

(a) The mechanics of capture for spray booth applications is primarily aerosol capture. Vapor/liquid equilibrium curves are not extremely favorable for vapor phase absorption at low vapor concentrations.

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(b) The principal advantages of emulsion scrubbing are lower viscosity, improved solids handling, and reduced oil throughput for distillation/recovery relative to heavy oil scrubbing. These are advantageous mainly for aerosol capture. The emulsion may actually inhibit vapor/liquid mass transfer to the oil phase, resulting in a less efficient recovery of vapor phase VOC's relative to conventional oil scrubbing.

(c) The alkalinity of the emulsion aqueous phase has resulted in hydrolysis of chlorinated hydrocarbons forming byproduct salts which build up in the system. This would require a continuous purge to prevent adverse impacts on emulsion formation/breaking behavior.

Considering the above factors, the complexity of the process, and the difficulty in projecting performance without laboratory data for chlorinated hydrocarbons, Nalco could not project anticipated costs or performance for the subject applications. Nalco and HPD could offer laboratory feasibility testing services, but did not recommend further study because the probability of success is low and the capital expenditures for the complex process are considered too high for small applications.

To confirm the determination from the previous WESTON study that conventional heavy oil scrubbing was not effective for low concentrations of VOC's, WESTON contacted a manufacture of heavy oil solvent recovery systems. Their response confirmed that conventional heavy oil scrubbing is not cost-effective in these applications. (14)

3.8.2 Conceptual design. The Nalco process is depicted in Figure 12. The design would be modified by replacing the fluid wall scrubber with a countercurrent packed tower scrubber.

3.8.3 VOC control efficiency. Approximately 65 to 70 percent VOC control efficiencies have been demonstrated in development studies for VOC's contained in paint overspray emissions which include a high aerosol fraction. Information on vapor phase capture potential is unavailable.

3.8.4 Reliability. If effective, conventional absorption systems typically give consistent and reliable performance. However, the Nalco system is more complex. Its first commercial unit is being installed in the near future and, thus, it has not had an operating history.

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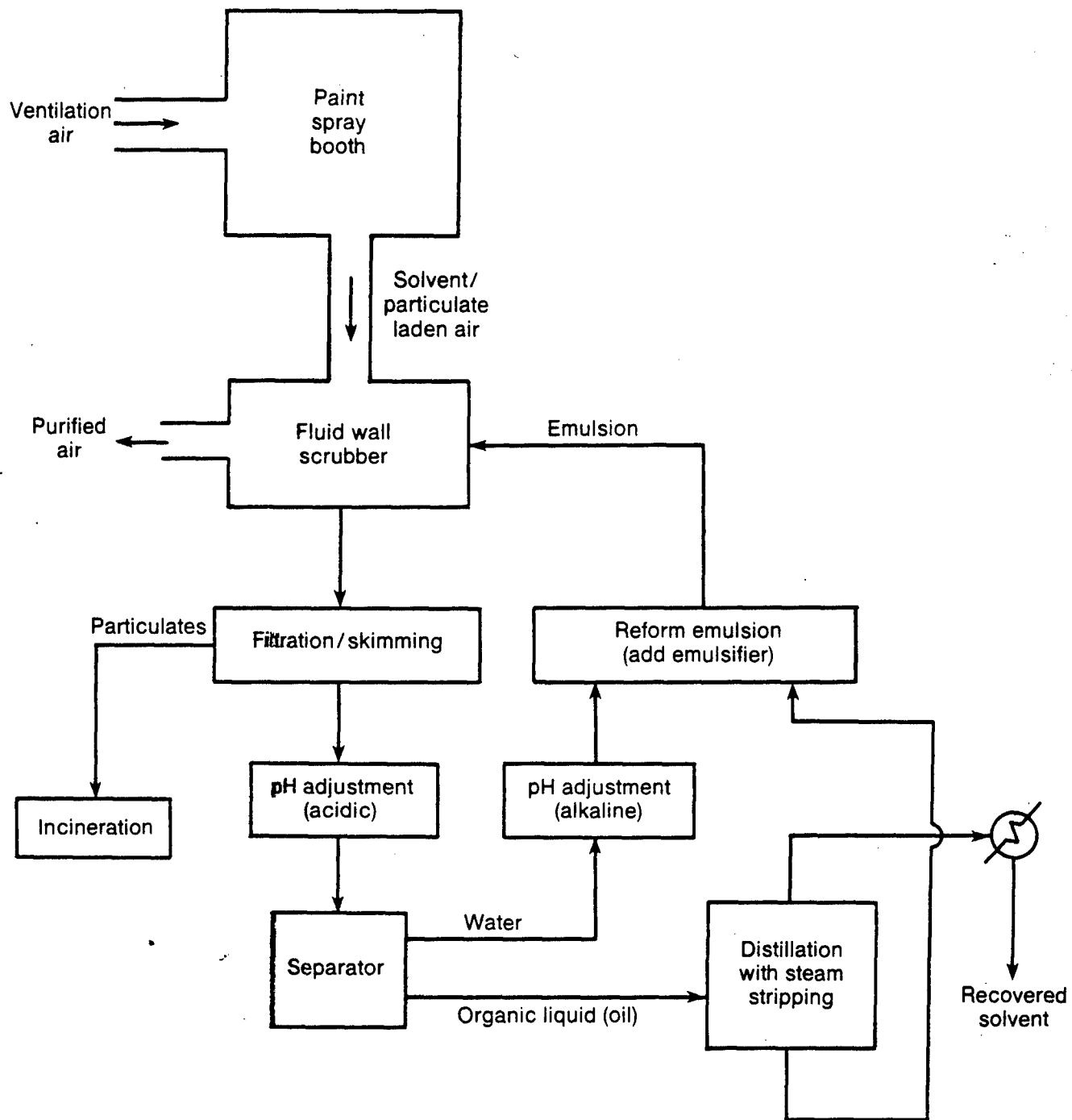
Figure 12. Oil/water emulsion absorption block flow diagram.

3.8.5 Ease of operation/maintenance. The Nalco process is complex and would require more operator attention than most conventional emission control systems. The unit processes are standard for the chemical process industry and would require staffing and training accordingly.

3.8.6 Transportability. The process is complex, therefore, it may be difficult to design and construct modular units.

3.8.7 Environmental issues. The primary environmental concern is performance. The technology would be acceptable if adequate performance can be achieved. The recovered VOC's would require off-site treatment/disposal. If salt build-up occurs, the aqueous phase would have to be purged, resulting in the generation of an aqueous phase saturated with chlorinated organics for off-site treatment/disposal.

3.8.8 Proprietary status. This is a patented proprietary process of Nalco.

3.8.9 Development time. The first commercial application for paint spray booth emission control will be installed in the near future. For the new applications considered in this study, chlorinated organics at low concentrations, extensive laboratory testing would be necessary to determine performance. Testing to select emulsion additives and determine vapor/liquid equilibrium data would be necessary. Pilot testing prior to scale-up would also be advisable. If resolution of anticipated development obstacles could be achieved, two or more years would be required to complete development for this application.

3.8.10 Estimated treatment costs. HPD Incorporated indicated that the smallest anticipated installation for paint spray booth applications would treat 100,000 cfm of air and require $2 to $3 million in capital expenditure. (13) One-third to one-half of this amount represents equipment costs. Capital and operating costs are sensitive to paint overspray loading. Since dilute VOC air streams have much lower loading rates, and the process configuration would change significantly, direct cost comparisons could not be made. Treatment costs were not projected for reasons discussed previously.

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4. COMPARATIVE ANALYSIS OF THE TECHNOLOGIES

Each technology was evaluated in Section 3 with respect to seven noncost criteria which addressed performance/implementation factors and an eighth criterion which addressed capital and operating cost. In this section, a comparative evaluation of the technologies is conducted to determine which technologies are candidates for research and development efforts and prospective IR process applications.

4.1 <u>Methodology for comparative evaluation</u>. The cost estimates are first compared for each application to determine which emerging technologies may be competitive with conventional technologies. The capital and operating costs are summarized and the overall cost, including initial capital outlays and future expenditures (discounted by the net interest rate), is calculated based on 1986 dollars. This overall cost, or net present worth, allows a fair comparison of alternatives which may be more capital intensive with those that have higher operating cost.

The technologies are then compared on the basis of each noncost criteria. The advantages and disadvantages of each technology are summarized, including the uncertainties which may impact successful development and implementation.

To conduct an objective comparison which promotes consideration on each criterion, a numerical ranking analysis was used. In this analysis, the relative importance of each criterion is considered by assigning a rating factor. This allows more emphasis to be placed on certain criteria, such as VOC control efficiency. A technology is evaluated by assigning a score to each criterion. These scores are multiplied by their respective rating factors. The total scores can then be used to provide a relative comparison of the various technologies.

The relative rating factors were developed using Table 12, which compares the importance of each criterion against each other one. A guideline for scoring the technologies was also developed. These guidelines, presented in Table 13, provide a benchmark for consistency in scoring the technologies.

The numerical scoring is intended only to serve as an aid to decisionmaking. Ultimately, a recommendation is made based on consideration of numerical scores, potential for reducing VOC emission control costs, and sound engineering judgement of the potential for successful technology development.

TABLE 12

TABLE 12. METHODOLOGY FOR DEVELOPMENT OF RATING FACTORS

	VOC Control Efficiency	Reliability	Ease of Op/M	Transportability	Environmental Issues	Proprietary Status	Development Time	Projected Treatment Costs	Summation	Rating Factor
VOC Control Efficiency	-	1/2	1	1	1	1	1	1	6.5	10
Reliability	1/2	-	1/2	1	1	1	1/2	1/2	5.0	8
East of Op/M	0	1/2	-	1	1/2	1	1	0	4.0	6
Transportability	0	0	0	-	1	1	1	0	3.0	5
Environmental Issues	0	0	1/2	0	-	1/2	1/2	1/2	2.0	3
Proprietary Status	0	0	0	0	1/2	-	0	0	.5	1
Development Time	0	1/2	0	0	1/2	1	-	1/2	2.5	4
Projected Treatment Costs	0	1/2	1	1	1/2	1	1/2	-	4.5	7

Rating System

1   = Criterion is comparatively more important than that given on top axis.
1/2 = Criteria are equally important.
0   = Criterion is less important than that given on top axis.

Assignment of Rating Factor

Final Rating Factor obtained by normalizing the summation to a maximum weighting factor of 10 and rounding off to the nearest whole number.

TABLE 13

GUIDELINES FOR SCORING TECHNOLOGIES

Criteria	Score of 3	Score of 2	Score of 1
VOC Control Efficiency	Demonstrated efficiency >90%	Demonstrated efficiency 70-90%	Demonstrated efficiency <70% or undetermined.
Reliability	Achieves consistent control efficiency of a fixed operating condition. Reliable, proven equipment.	Some difficulties in maintaining treatment efficiencies or stable equipment operation. No long term equipment history.	Inconsistent treatment efficiency at fixed operating conditions; inability to handle variations in contaminant loading. Complex, unreliable equipment.
Ease of Operation/ Maintenance	Requires minimal operator attention; routine equipment maintenance required.	Requires some operator attention to adjust operating conditions; some training needed for specialized O&M procedures.	Requires full-time operator attention; specialized training requirements; high downtime and maintenance.
Transportability	Standard units are modular; minimal field assembly/disassembly required; fully portable units are feasible.	Modular units would require extensive design effort; substantial field assembly/disassembly required.	Complex process not readily modularized; extensive field assembly/disassembly required.
Environmental Issues	No treatment by-products emitted.	Some treatment by-products produced but controllable.	Opposition to permit is likely; undefined or untreatable hazardous treatment by-products.
Proprietary Status	Not patented; equipment available from many vendors.	Not patented but closely held design and performance information.	Patented and closely held proprietary design and performance information.
Development Time	None; commercial equipment available; design information available.	A year or two; promising based on initial data.	Several years likely; known problems require resolution.
Estimated Treatment Costs	Less expensive than conventional fume incineration.	Equivalent to conventional fume incineration.	More expensive than conventional fume incineration.

4.2 Comparison of estimated cost. Capital and operating cost estimates developed in Section 3 are compared in Tables 14 through 17 for each IR treatment process application studied. Net present worth cost was calculated based on a simple interest rate of 10 percent per year which represents the present value of future operating costs (applied where operations will continue longer than one year). The net present worth allows consideration of capital and operating cost on an equivalent basis. Emission control cost was also expressed in $/ton of VOC abated which allows a comparison between sites. This results in underestimating the dollars per ton cost for potentially less efficient technologies (e.g., UV/ozone/ catalytic oxidation).

The comparison of estimated costs for ISV at Site D (Table 14) show that carbon adsorption, incineration, catalytic oxidation, and UV/ozone/catalytic oxidation would be in a similar cost range with catalytic oxidation exhibiting the lowest cost. For this short-term application (10 months), fume incineration is competitive because energy consumption costs for incineration are not high relative to capital and other operating costs. Clearly, KPR/incineration and PURASIV would not be competitive due to high capital cost. Heat recovery options for incineration and catalytic oxidation are not cost-effective due to the short period of operation. Off-gas scrubbing, if required, would significantly increase costs for oxidation and incineration processes.

The estimated costs for ISV at Site G (Table 15) show a wider variation in net present worth between technologies due to larger air flow rates. Catalytic oxidation would potentially have a cost advantage over incineration but would be more costly than carbon adsorption. UV/ozone/catalytic oxidation no longer appears to be competitive for this application based on these projections. PURASIV and KPR/incineration remain uncompetitive primarily due to the high capital costs. Similarly, heat recovery is not cost-effective and off-gas scrubbing would significantly increase costs for oxidation and incineration processes.

The estimated costs for LTTS (Table 16) exhibit a pattern similar to ISV at Site G, with catalytic oxidation showing a potentially slight cost advantage over carbon adsorption, incineration and UV/ozone/ catalytic oxidation. The results for other technologies and options are similarly uncompetitive.

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TABLE 14. COST ESTIMATE COMPARISON
IN SITU VOLATILIZATION - SITE D

	Capital cost	10-month operating cost[a]	Net present worth[b]	$ per ton of VOC treated[c]
Carbon adsorption	$270,000	$ 80,000	$ 350,000	$ 22,000
Fume incineration:[d]				
Option A	136,000	274,000	410,000	25,000
Option B	597,000	116,000	713,000	44,000
Option C	766,000	175,000	941,000	58,000
PURASIV[e]	~750,000	~250,000	~1,000,000	~62,000
KPR carbon fiber/ incineration[f]	775,000	120,000	895,000	56,000
Catalytic oxidation:[d]				
Option A	178,000	160,000	338,000	21,000
Option B	263,000	112,000	375,000	23,000
Option C	913,000	196,000	1,109,000	69,000
UV/ozone/catalytic oxidation (Ultrox)[g]	325,000	75,000	400,000	25,000

[a] Operating cost is for the expected 10-month duration of operation at Site D.
[b] Net present worth = Annual operating costs + capital costs.
[c] $ per ton VOC treated = net present worth/total tons of VOC treated.
[d] Option A includes an incinerator with no scrubber or heat recovery. Option B includes incinerator and heat recovery. Option C includes incinerator, heat recovery, quench, and caustic scrubber. 75% heat recovery for fume incineration and 42% for catalytic oxidation.
[e] Unit design would be out of the range of previous experience. Order-of-magnitude costs presented for comparison.
[f] Cost extrapolated from generic applications sized at 10,000 to 20,000 cfm. Smaller units are not generally considered cost-effective. No off-gas scrubbing included.
[g] Cost estimated by best engineering judgment of Ultrox. No design or performance data available for these applications. No off-gas scrubbing included.

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TABLE 15.   COST ESTIMATE COMPARISON
IN SITU VOLATILIZATION - SITE G

	Capital cost	Annual operating cost	Net present worth[a]	$ per ton of VOC treated[b]
Carbon adsorption	$ 372,000	$177,000	$ 549,000	$ 9,000
Fume Incineration[c]:				
Option A	193,000	585,000	778,000	13,000
Option B	775,000	247,000	1,022,000	17,000
Option C	1,021,000	340,000	1,361,000	23,000
PURASIV[d]	~1,000,000	~300,000	~1,300,000	~22,000
KPR carbon fiber[e]	885,000	190,000	1,075,000	18,000
Catalytic oxidation[c]:				
Option A	255,000	394,000	649,000	11,000
Option B	380,000	257,000	637,000	11,000
Option C	1,340,000	392,000	1,732,000	29,000
UV/ozone/catalytic oxidation (Ultrox)[e,f]	648,000	143,000	791,000	13,000

[a]Net present worth = Annual operating costs + capital costs.
[b]$ per ton VOC treated = net present worth/total tons of VOC treated.
[c]Option A includes an incinerator with no scrubber or heat
recovery. Option B includes incinerator and heat recovery. Option C
includes incinerator, heat recovery quench, and caustic scrubber. 75%
heat recovery for fume incineration and 42% for catalytic oxidation.
[d]Unit design would be out of the range of previous experience. Order-
of-magnitude costs presented for comparison.
[e]Cost extrapolated from generic applications sized at 10,000 to 20,000
cfm. Smaller units are not generally considered cost-effective. No off-
gas scrubbing included.
[f]Cost estimated by best engineering judgment of Ultrox. No design or
performance data available for these applications. No off-gas scrubbing
included.

TABLE 16. COST ESTIMATE COMPARISON
LTTS

	Capital cost	Annual operating cost	Net present worth[a]	$ per ton of VOC treated[b]
Carbon adsorption	$236,000	$112,000	$348,000	$12,000
Fume Incineration[c]:				
Option A	150,000	156,000	306,000	11,000
Option B	601,000	94,000	695,000	24,000
Option C	775,000	165,000	940,000	32,000
PURASIV[d]	~750,000	~250,000	~1,000,000	~34,000
KPR carbon fiber[e]	715,000	129,000	844,000	29,000
Catalytic oxidation[c]:				
Option A	150,000	77,000	227,000	8,000
Option B	214,000	65,000	279,000	10,000
Option C	714,000	156,000	870,000	30,000
UV/ozone/catalytic oxidation (Ultrox)[e,f]	209,000	79,000	288,000	10,000

[a]Net present worth = Annual operating costs + capital costs.
[b]$ per ton VOC treated = net present worth/total tons of VOC treated.
[c]Option A includes an incinerator with no scrubber or heat recovery. Option B includes incinerator and heat recovery. Option C includes incinerator, heat recovery, quench, and caustic scrubber. 75% heat recovery for fume incineration and 42% for catalytic oxidation.
[d]Unit design would be out of the range of previous experience. Order-of-magnitude costs presented for comparison.
[e]Cost extrapolated from generic applications sized at 10,000 to 20,000 cfm. Smaller units are not generally considered cost-effective. No off-gas scrubbing included.
[f]Cost estimated by best engineering judgment of Ultrox. No design or performance data available for these applications. No off-gas scrubbing included.

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TABLE 17. COST ESTIMATE COMPARISON
GWAS

	Capital cost	Annual operating cost	Net present worth[a]	$ per ton of VOC treated[b]
Carbon adsorption	$135,000	$ 49,000	$ 436,000	$ 50,000
Fume Incineration[c]:				
Option A	113,000	95,000	697,000	80,000
Option B	451,000	70,000	881,000	101,000
Option C	585,000	114,000	1,285,000	148,000
PURASIV[d]	~750,000	~250,000	~2,286,000	~263,000
KPR carbon fiber[e]	615,000	122,000	1,371,000	158,000
Catalytic oxidation[c]:				
Option A	113,000	67,000	525,000	60,000
Option B	163,000	57,000	513,000	59,000
Option C	565,000	117,000	1,284,000	148,000
UV/ozone/catalytic oxidation (Ultrox)[e,f]	108,000	47,000	397,000	46,000

[a]Net present worth includes annual operating costs and present worth capital costs.

[b]$ per ton VOC treated = net present worth/total tons contaminant treated.

[c]Option A includes an incinerator with no scrubber or heat recovery. Option B incudes incinerator and heat recovery. Option C includes incinerator, heat recovery, quench, and caustic scrubber, although a caustic scrubber is not expected to be needed. 75% heat recovery for fume incineration and 42% for catalytic oxidation.

[d]Unit design would be out of the range of previous experience. Order-of-magnitude costs presented for comparison.

[e]Cost extrapolated from generic applications sized at 10,000 to 20,000 cfm. Smaller units are not generally considered cost-effective. No off-gas scrubbing included.

[f]Cost estimated by best engineering judgment of Ultrox. No design or performance data available for these applications. No off-gas scrubbing included.

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The estimated costs of GWAS presented in Table 17 indicate that catalytic oxidation and UV/ozone/catalytic oxidation appear to have a significantly lower net present worth cost than fume incineration but would not significantly improve on carbon adsorption costs. KPR carbon fiber/incineration and PURASIV would be far too expensive for the small air flow GWAS stream due to the high capital costs for these complex technologies. It is unlikely that caustic scrubbing would be required for the GWAS application due to the low rate of HCl generated upon oxidation for fume incineration and catalytic oxidation, although the costs for this option are presented for completeness. Heat recovery options for incineration and catalytic incineration do not appear to be worth the additional investment for GWAS due to the low-energy utilization relative to capital cost for the low air flow application.

These comparative results indicate a potential for catalytic oxidation to be competitive with conventional technologies for some applications. Carbon adsorption, a conventional technology, remains cost competitive, but may have other noncost drawbacks, particularly performance and disposal of by-products. Where high-performance destruction is desired, catalytic oxidation can potentially provide significant cost savings relative to fume incineration.

The UV/ozone/catalytic oxidation process appears competitive based on these very preliminary cost estimates, particularly for low air flow applications. Since this system is small in size, modular, and all-electric, the potential exists to achieve even lower installation costs than these projections would indicate. However, it should be noted that the estimated costs presented for UV/ozone/catalytic oxidation involve a higher level of uncertainty and could be low due to the lack of firm cost/performance data for these technologies. Extensive testing and the development of firm design criteria remain to be completed before the potential for low-cost UV/ozone/catalytic treatment can be accurately determined.

Generally, if caustic scrubbing for oxidation off-gases would be required, costs for catalytic oxidation would rise significantly. Although cost data was not available for scrubbing acidic off-gases from KPR and Ultrox systems, similar cost increases for caustic scrubbing are likely for these technologies.

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In order to demonstrate the comparative costs of these technologies for a broader range of potential applications, the costs were presented on a common basis. Costs were tabulated for each air flow evaluated for an operating life of 1 year and 10 years (see Tables 18 and 19).

For the low concentration VOC emission sources considered in this study, air flow is most often the largest impact on capital and operating costs. To illustrate the effects of emission source flow rate on the various technology costs, plots of total present worth costs versus emission source air flow were developed.

Figure 13 graphs projected total present worth cost versus air flow for the one year operating life. Incineration and catalytic oxidation curves were plotted for the base case without heat recovery or caustic scrubbing. This graph confirms that the catalytic oxidation cost should be competitive in these applications and that UV/ozone/catalytic oxidation has the potential for low cost in some of these applications.

Figure 14 plots the total present worth cost for a 10-year operating life. This illustrates the cost relationship for a longer emission control system operating life.

Since Table 18 indicates that heat recovery is the more cost effective option for fume incineration and fluidized bed catalytic oxidation at the 10-year operating life, the curves on Figure 14 represent the heat recovery option.

For the longer duration of operation, the advantages of catalytic oxidation and UV/ozone/catalytic oxidation over incineration becomes clearer due to the payback of lower energy use over time. This plot also shows that the KPR/incineration technology begins to be competitive with longer duration of operation and higher flow rates. The flatter slope of the curve for this technology indicates that it may be competitive for air flow rates between 10,000 and 20,000 cfm at a 10-year operating life.

This analysis indicates that catalytic oxidation and UV/ozone/catalytic oxidation remain cost competitive for long-term operations. While the 10-year operation analysis was based on control equipment operating at a single site, the trend from a 1-year to 10-year operation gives an indication of the potential savings for transportable units. When off-gas scrubbing is not necessary, connection and ancillary equipment are low. These technologies, particularly UV/ozone/catalytic oxidation, have fewer utility connections and ancilliary equipment requirements than carbon adsorption. As a result, the installation/disassembly costs for reuse on numerous sites may be lower.

TABLE 18.   TOTAL PRESENT WORTH COSTS FOR 1-YEAR OPERATION

| | Estimated Present Worth Costs | | | |
Technology	ISV Site D	ISV Site G	LTTS	GWAS
Carbon adsorption	$ 366,000	$ 549,000	$ 348,000	$ 184,000
Fume Incineration[a]:				
Option A	465,000	778,000	306,000	208,000
Option B	736,000	1,022,000	695,000	521,000
Option C	976,000	1,361,000	940,000	699,000
PURASIV	~1,000,000	~1,300,000	~1,000,000	~1,000,000
KPR carbon fiber	919,000	1,075,000	844,000	738,000
Catalytic oxidation:[b]				
Option A	371,000	649,000	227,000	180,000
Option B	398,000	637,000	279,000	220,000
Option C	1,148,000	1,732,000	870,000	682,000
UV/ozone/catalytic oxidation (Ultrox)	415,000	791,000	288,000	155,000

[a]Option A includes an incinerator with no scrubber or heat recovery. Option B incudes incinerator and heat recovery. Option C includes incinerator, heat recovery, quench, and caustic scrubber. A 75 percent heat recovery factor is assumed.
[b]Same options as for fume incineration except that a 42 percent heat recovery factor was used.

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TABLE 19.   TOTAL PRESENT WORTH COSTS FOR 10-YEAR OPERATION

	Estimated Present Worth Costs			
Technology	ISV Site D	ISV Site G	LTTS	GWAS
Carbon adsorption	$ 860,000	$1,460,000	$ 924,000	$ 436,000
Incineration[a]:				
Option A	2,158,000	3,788,000	1,109,000	697,000
Option B	1,451,000	2,293,000	1,179,000	881,000
Option C	2,056,000	3,110,000	1,789,000	1,285,000
PURASIV	~2,286,000	~2,843,000	~2,286,000	~2,286,000
KPR carbon fiber	1,660,000	2,052,000	1,508,000	1,371,000
Catalytic oxidation[b]:				
Option A	1,364,000	2,676,000	623,000	525,000
Option B	1,093,000	1,959,000	613,000	'513,000
Option C	2,357,000	3,749,000	1,673,000	1,284,000
UV/ozone/catalytic oxidation (Ultrox)	878,000	1,527,000	694,000	397,000

[a]Option A includes an incinerator with no scrubber or heat recovery. Option B incudes incinerator and heat recovery. Option C includes incinerator, heat recovery, quench, and caustic scrubber. A 75 percent heat recovery factor is assumed.
[b]Same options as for fume incineration except that a 42 percent heat recovery factor was used.

FIGURE 13. COST VERSUS FLOWRATE.

FOR ONE YEAR OPERATION
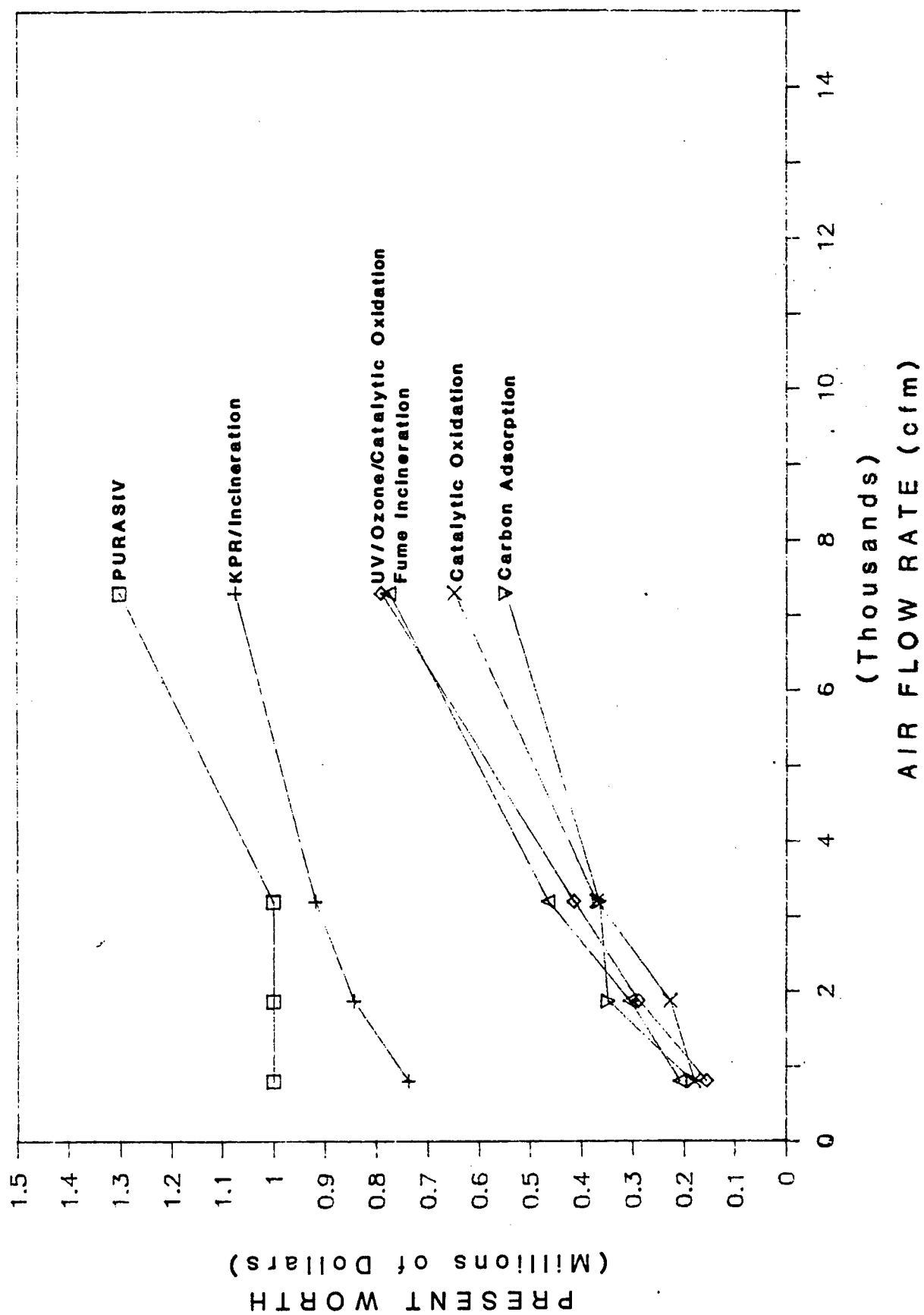
FIGURE 14. COST VERSUS FLOWRATE

FOR TEN YEAR OPERATION

□ PURASIV

△ Fume Incineration with Heat Exchange

+ KPR/Incineration

✕ Catalytic Oxidation with Heat Exchange

◇ UV/Ozone/Catalytic Oxidation
◇ Carbon Adsorption

PRESENT WORTH
(Millions of Dollars)

AIR FLOW RATE (cfm)
(Thousands)
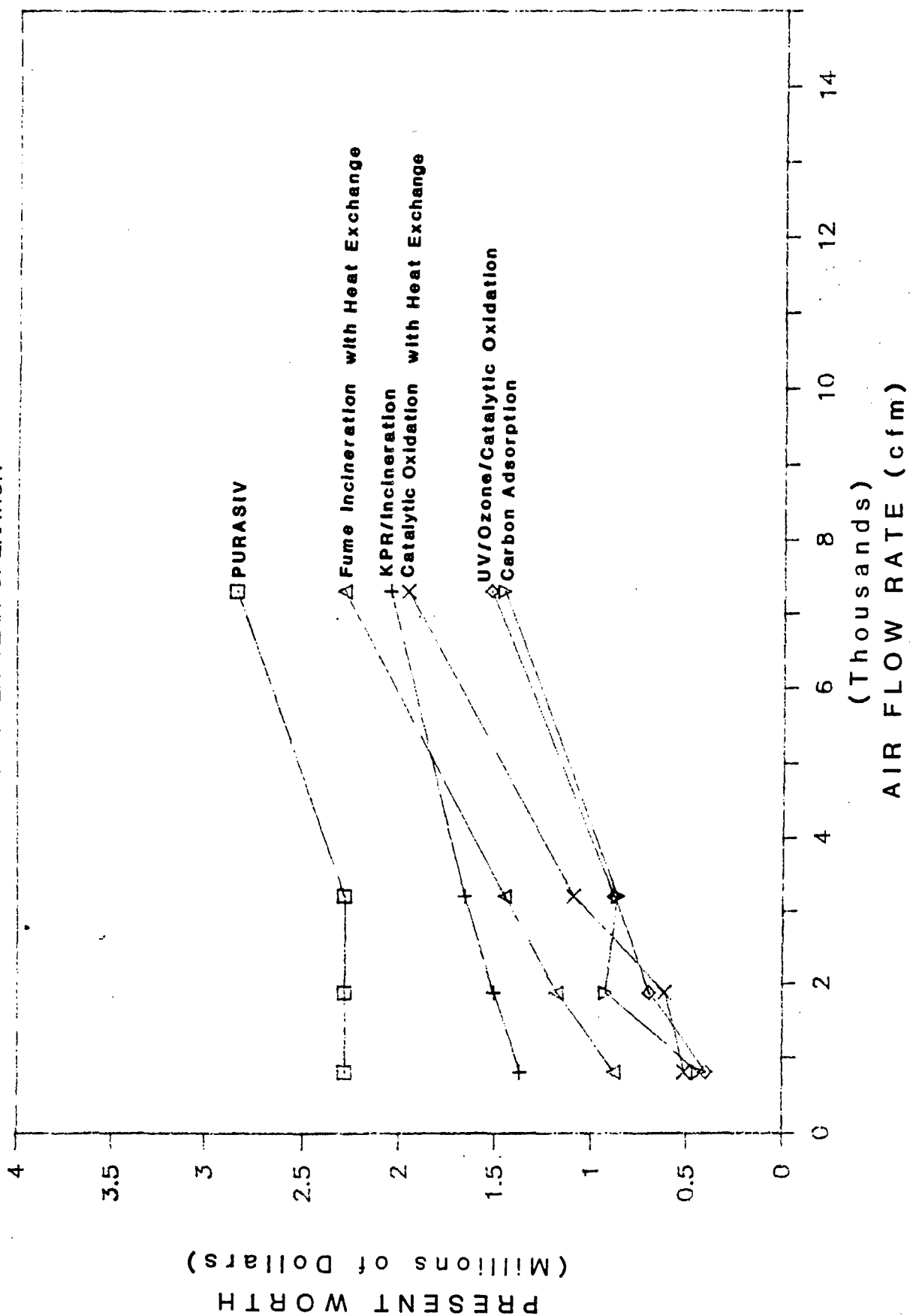
4.3   <u>Overall technology comparison</u>.   The technology evaluations in Section 3, identified the advantages and disadvantages for each conventional and novel technology based on a wide range of criteria. They also identified the uncertainties which must be addressed in the development and/or implementation of each technology. These advantages, disadvantages, and uncertainties are summarized for each technology in Table 20.

In the following subsections technologies are directly compared for each evaluation criterion. This comparison was used to numerically score each technology and these scores appear in Table 21 for comparative purposes.

4.3.1   VOC control efficiency.   Fume incineration offers the highest potential control efficiency (>99.99 percent). Fluidized bed catalytic oxidation also offers very high efficiencies (>99 percent) and at a much lower operating temperature, particularly for nonchlorinated VOC air streams. Consistent performance for handling mixed chlorinated VOC streams has not been demonstrated. Carbon adsorption may have somewhat lower efficiencies (85 to 90 percent) in the low concentration applications. KPR/incineration performance is expected to be as high or higher than conventional carbon adsorption since the regeneration gases are directly incinerated. Likewise, PURASIV is expected to have higher efficiency due to the recirculation of regeneration gas in a continuous regeneration/condensation loop. The UV/ozone/ catalytic oxidation system performance in early tests has been low without ozone addition (<70 percent) and resulted in byproduct formation with ozone addition. While performance may be improved with further development effort, it is presently undemonstrated. The conceptual oil/water emulsion scrubbing process performance is presently undefined but is likely to have poor control efficiencies (<70 percent).

4.3.2   Reliability.   The conventional technologies have demonstrated a high level of reliability. Fluidized bed catalytic oxidation equipment also has a history of reliable application and consistent performance for handling non-chlorinated VOC air streams in industrial applications. Potential catalyst fouling with chlorinated VOC streams is a reliability concern. PURASIV performance may be consistent under steady operating conditions, but the complexity of the process makes equipment reliability a concern. KPR/incineration may prove to be reliable but is just being introduced commercially in this country. UV/ozone/catalytic oxidation is not commercially available and reliability has not been established. The oil/water emulsion scrubbing system is a complex process which has not yet been demonstrated, so reliability is uncertain.

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TABLE 20. SUMMARY OF INDIVIDUAL TECHNOLOGY EVALUATIONS

Technology	Advantages	Disadvantages	Uncertainties
Carbon Adsorption	• Proven Conventional Technology • Reliable for Steady Feed Composition • Readily Transportable • Cost Competitive for Most Applications • Variety of On-Site/Off-Site Regeneration Options	• Low Adsorption Efficiencies at Low VOC Concentrations • Disposal of Spent Carbon or Carbon Regeneration Residues Required • Variable Loading Affects Operator Attention, Operating Conditions • Sensitive to Humidity, Temperature	
Fume Incineration	• Proven Conventional Technology • High Destruction Efficiencies • Highly Reliable • High Performance with Variable Feed Composition • Readily Transportable • Simple Operation • Cost Competitive for Short Term, Low Flow Applications	• High Operating Costs for High Flow, Long Term Applications • High Sensitivity to Fuel Costs	• HCl Emissions May Require Scrubber at High Cost Penalty
PURASIV Carbon Bead System	• Closed Regeneration Loop May Improve Treatment Efficiencies Compared with Conventional Carbon Systems • High Concentration in Regeneration Stream - Could Couple With Incineration	• Extremely High Capital Costs • Complex Process • Proprietary Process (Purasiv-Kureja) • High Flow Systems Available Only Through Overseas Company • Extensive Engineering Design Effort Necessary for Development of Low Flow Unit	• Uncertain Technical Feasibility for Low Flow, Low Concentrations
KPR - Carbon Fiber/ Incineration	• Direct Input of Regeneration Stream into Incinerator Results in Higher Treatment Efficiencies • Continuous Regeneration Flow to Incinerator • Proven Commercial Units (in Japan) for High Flow Applications	• High Capital Costs • Proprietary Process (MET-PRO) • Non-Competitive for Low Flow, Short Term Applications • Variable Loading Affects Operator Attention, Operating Conditions • Sensitive to Humidity, Temperature	• Uncertain Performance of Carbon Fiber Technology for Low Concentration • HCl Emission May Require Scrubbing at High Cost Penalty

TABLE 20. SUMMARY OF INDIVIDUAL TECHNOLOGY EVALUATIONS

Technology	Advantages	Disadvantages	Uncertainties
Carbon Adsorption	• Proven Conventional Technology • Reliable for Steady Feed Composition • Readily Transportable • Cost Competitive for Most Applications • Variety of On-Site/Off-Site Regeneration Options	• Low Adsorption Efficiencies at Low VOC Concentrations • Disposal of Spent Carbon or Carbon Regeneration Residues Required • Variable Loading Affects Operator Attention, Operating Conditions • Sensitive to Humidity, Temperature	
Fume Incineration	• Proven Conventional Technology • High Destruction Efficiencies • Highly Reliable • High Performance with Variable Feed Composition • Readily Transportable • Simple Operation • Cost Competitive for Short Term, Low Flow Applications	• High Operating Costs for High Flow, Long Term Applications • High Sensitivity to Fuel Costs	• HCl Emissions May Require Scrubber at High Cost Penalty
PURASIV Carbon Bead System	• Closed Regeneration Loop May Improve Treatment Efficiencies Compared with Conventional Carbon Systems • High Concentration in Regeneration Stream – Could Couple With Incineration	• Extremely High Capital Costs • Complex Process • Proprietary Process (Purasiv-Kureja) • High Flow Systems Available Only Through Overseas Company • Extensive Engineering Design Effort Necessary for Development of Low Flow Unit	• Uncertain Technical Feasibility for Low Flow, Low Concentrations
KPR – Carbon Fiber/ Incineration	• Direct Input of Regeneration Stream into Incinerator Results in Higher Treatment Efficiencies • Continuous Regeneration Flow to Incinerator • Proven Commercial Units (in Japan) for High Flow Applications	• High Capital Costs • Proprietary Process (MET-PRO) • Non-Competitive for Low Flow, Short Term Applications • Variable Loading Affects Operator Attention, Operating Conditions • Sensitive to Humidity, Temperature	• Uncertain Performance of Carbon Fiber Technology for Low Concentration • HCl Emission May Require Scrubbing at High Cost Penalty

TABLE 21.

COMPARATIVE RANKING OF TECHNOLOGIES

Criteria	Rating Factor	Carbon Adsorption	Fume Incineration					Catalytic Oxidation			
			-	Heat Recovery	Heat Recovery and Scrubber	PURASIV	KPR	-	Heat Recovery	Heat Recovery and Scrubber ULTROX	NALCO
VOC Control Efficiency	10	2	3	3	3	3	3	2	2	2	1
Reliability	8	3	3	3	3	2	2	2	2	2	1
Ease of O&M	6	2	3	3	2	1	3	3	3	2	1
Transportability	5	2	3	3	2	1	2	3	3	2	1
Environmental Issues	3	2	2	2	3	2	2	2	2	3	2
Proprietary Status	1	3	3	3	3	1	1	1	1	1	1
Development Time	4	3	3	3	3	2	2	2	2	2	1
Projected Treatment Costs	7	3	2	2	1	1	1	3	3	1	1
Σ(rating factor)(technology score)		108	122	122	104	79	96	105	105	83	47

4.3.3 Ease of operation/maintenance. Ease of operation and maintenance is rated highest for fume incineration and fluidized bed catalytic oxidation (when off-gas scrubbing is not used) because they are automated, self-regulating processes with no by-product handling requirements. They were rated slightly lower with the addition of caustic scrubbing due to the added complexity of raw material and spent caustic handling. KPR/incineration is rated highly, although more operator attention for monitoring and adjustment of operating conditions may be necessary for highly variable loading applications. Carbon adsorption is rated slightly lower since it requires operator attention for both monitoring and handling of spent carbon regeneration residues. UV/ozone/catalytic oxidation is reported to be readily operable but the possible need to monitor and adjust operating conditions and the uncertainty in the operability of the fully developed process resulted in a slightly lower rating. PURASIV was considered difficult to operate and maintain due to the complexity of the process. Oil/water emulsion scrubbing was also given a low rating due to complexity of the process.

4.3.4 Transportability. The carbon adsorption system evaluated in this study (using steam regeneration) is given a moderate rating. Although modular units are readily available, extensive ancillary equipment (package steam boilers, condensate receivers, etc.) installation would be necessary. If on-site regeneration is not used (i.e., spent carbon disposed off-site) a higher rating would be appropriate. Incineration and catalytic oxidation without off-gas scrubbing are readily transportable modular units with little field erection required. Off-gas scrubbing would increase process complexity and field assembly requirements. UV/ozone/catalytic oxidation is expected to be a small, readily transportable unit. An all-electric unit could be used, since heat input requirements are minimal. This would allow rapid setup with minimal installation. KPR/incineration was given a moderate rating since the system is more complex and standard units are presently sized for larger installations. The PURASIV and oil/water emulsion scrubbing technologies were given the lowest ratings since they require field assembly of numerous process components.

4.3.5 Environmental issues. Carbon adsorption, PURASIV, and oil/water emulsion scrubbing were given a moderate score due to the generation of contaminated condensate and/or solvent which will require further off-site treatment/disposal. Incineration, KPR/incineration, UV/ozone/catalytic oxidation, and catalytic oxidation without scrubbing were given moderate scores due to the emission of HCl to the atmosphere. With the addition of off-gas scrubbing, fume incineration and fluidized bed catalytic oxidation were scored highly.

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4.3.6 Proprietary status. The conventional technologies are widely available for use without restriction. The novel technologies were rated low because the process, or some key component of the process (e.g., catalyst) was patented and information on design and performance are not generally available.

4.3.7 Development time. The conventional technologies require no further development. PURASIV and KPR/incineration are commercially available for large air flow applications, but extensive engineering design and demonstration studies would be required to apply them to the smaller air flow lower concentration chlorinated VOC sources studied. Fluidized bed catalytic oxidation has been commercially applied to chlorinated hydrocarbon streams with similar air flow rates but typically for higher concentrations of VOC. Performance for mixed VOC streams is also uncertain and demonstration studies may be desirable prior to general use for these applications. UV/ozone/catalytic oxidation and oil/water emulsion scrubbing would require extensive laboratory and pilot testing on a broad range of compounds and operating conditions to determine performance and develop design criteria prior to implementation.

4.3.8 Estimated treatment cost. Fume incineration was used as a basis for comparison in the scoring for projected cost. Carbon adsorption, fluidized bed catalytic oxidation, and UV/ozone/catalytic oxidation were rated better due to generally lower projected cost. PURASIV, KPR/incineration, and oil/water emulsion scrubbing were rated lower due to projected higher costs.

4.3.9 Numerical ranking. The numerical scores for each technology based on an evaluation were presented in Table 21. The technologies are ranked from highest score to lowest as follows:

(a) Fume Incineration.
(b) Carbon adsorption.
(c) Catalytic oxidation.
(d) KPR/incineration.
(e) PURASIV.
(f) UV/ozone/catalytic (Ultrox).
(g) Emulsion scrubbing (Nalco).

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5. RESULTS AND CONCLUSIONS

5.1 <u>Results of comparative analysis and recommendations.</u>
Fluidized bed catalytic oxidation was ranked highest of the
novel technologies investigated. This technology has the
potential for high control efficiency and reliability. The
process can be designed to be readily transported and reused.
Where high-efficiency and reliability are necessary, catalytic
oxidation could be more cost-effective compared to convention
fume incineration. It is an attractive candidate for short-term
technology development and demonstration.

The second highest ranked novel technology was KPR carbon
fiber adsorption/incineration. However, this technology appears
to be more expensive than conventional alternatives for the
applications investigated. KPR is only expected to be cost-
effective as the size of the emission source and the duration
of operation increase. If applications for 20,000 cfm of flow
or more and 5 years of operation or more do arise, KPR should
be investigated further. The technology could be implemented
with less development effort.

UV/ozone/catalytic oxidation was rated relatively low due
to uncertainties resulting from its early stage of development.
VOC control efficiency has not been demonstrated for the
compounds considered in this study. Where high efficiencies
have been achieved in pilot testing, byproduct formation has
occurred. While the potential for obtaining satisfactory
performance exists, extensive development efforts are neces-
sary. This technology is also proprietary. The preliminary cost
data presented involves higher uncertainty, but it shows that
significant improvements in treatment cost may be achieved. The
process can be operated using only electricity as a power
source and is constructed as a compact modular unit that can be
readily transported for reuse on other sites. These features
would make it possible to reuse the equipment with low instal-
lation and disassembly costs. If portable units are feasible at
little increase in capital cost, as anticipated, the costs
presented here could be reduced by as much as 40 percent. Thus,
this is considered an attractive candidate for long-term
technology development.

The emulsion scrubbing technology received the lowest
relative rating. The probability of achieving adequate VOC
control efficiency is low due to technical limitations.

Of the conventional technologies, carbon adsorption may
provide low cost VOC emission control for the four applica-
tions studied, but lower control efficiency and the management
of spent carbon are disadvantages.

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5.2 <u>Conclusions and recommendations</u>. Five emerging VOC air emission control technologies were evaluated for four IR air emission control sources. These were compared with two conventional control technologies (carbon adsorption and fume incineration). Two of the five novel technologies have the potential to provide good treatment performance at low cost in some IR treatment process applications.

Fluidized bed catalytic oxidation is an excellent technology where high destruction efficiency and reliability is required. It can be cost-effective in many applications where fume incineration is presently used for chlorinated organics. The unit has been commercially applied by ARI International for higher concentration applications, and can be immediately applied on a demonstration basis.

Where lower control efficiencies and waste product generation/disposal are acceptable, carbon adsorption is cost competitive and should continue to be applied.

UV/ozone/catalytic oxidation holds the potential for low-cost emission control. Due to its operation at near ambient temperatures, operating costs are considerably lower than thermal oxidation processes. Fully modular, all-electric units are envisioned by Ultrox, the technology's developer. This may result in the product of a fully portable unit which would minimize installation costs with little increase in equipment costs. If this can be achieved, implementation costs could be lowered well below all other technologies considered in this study. The pilot testing performed to date indicate that high potential destruction efficiencies are achievable, but byproduct formation occurs. This problem should be addressed in further development efforts.

WESTON recommends the following novel technologies for USATHAMA development efforts:

(a) Short-term development/demonstration: fluidized bed catalytic oxidation.
(b) Long-term development: UV/ozone/catalytic oxidation.

The other technologies evaluated do not warrant development effort at this time for applications of the scale investigated. If large air flow emission applications arise, the KPR/incineration process should be explored further.

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APPENDIX A

COST ESTIMATE CALCULATION TABLES

TABLE A-1. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CARBON ADSORPTION/STEAM REGENERATION AT SITE D

Capital	Cost
Carbon adsorption/regeneration unit ($85,000 base unit x 2.5 installation factor) (air preheater at $500 installed)	$ 213,000
Portable steam generator (1,530 lb/hr at 9 psi; 45 boiler hp)	17,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Ancillary equipment (2.0 installation factor) (water supply tank with chiller 3,000 gal) (solvent receiver tank FRP 6,000 gal) (water receiver tank FRP 6,000 gal)	7,000 8,800 8,800
Total	270,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/man-year) (additionally, supervision is 25 percent of operator)	25,000
Maintenance (6 percent of capital cost)	16,200
Propane (2,700 gal at $1.25/gal)	3,400
Power (15 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	4,000
Disposal of condensed water Treatment (22,632 gals at $0.25/gal) Transportation (400 miles at $4/loaded mile x 5 loads)	13,700
Disposal of recovered solvent Treatment (32,200 lb at $0.42/lb) Transportation (400 miles at $3.50/loaded mile x 1 load)	15,000
Monitoring (52 samples; approximately $350 each)	18,000
Total	$ 96,000

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TABLE A-2. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CARBON ADSORPTION/STEAM REGENERATION AT SITE G

Capital	Cost
Carbon adsorption/regeneration unit ($127,000 base unit x 2.5 installation factor) (air preheater at $500 installed)	$ 318,000
Portable steam generator (1,230 lb/hr at 9 psi; 36 boiler hp)	14,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Ancillary equipment (2.0 installation factor) (water supply tank with chiller 3,000 gal) (solvent receiver tank FRP 6,000 gal) (water receiver tank FRP 6,000 gal)	7,000 8,800 8,800
Total	372,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/man-year) (additionally, supervision is 25 percent of operator)	25,000
Maintenance (6 percent of capital cost)	22,300
Propane (9,720 gal at $1.00/gal)	9,700
Power (15 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	4,000
Disposal of condensed water Treatment (78,175 gals at $0.25/gal) Transportation (400 miles at $4/loaded mile x 16 loads)	45,100
Disposal of recovered solvent Treatment (118,000 lb at $0.42/lb) Transportation (400 miles at $3.50/loaded mile x 2 loads)	52,400
Monitoring (52 samples; approximately $350 each)	18,000
Total	$ 177,000

TABLE A-3.   DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CARBON ADSORPTION/STEAM REGENERATION AT LTTS

Capital	Cost
Carbon adsorption/regeneration unit ($68,000 base unit x 2.5 installation factor) (air preheater at $500 installed)	$ 170,000
Pretreatment cooler/condenser	6,000
Baghouse	10,000
Portable steam generator (900 lb/hr at 9 psi; 27 boiler hp)	12,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Ancillary equipment (2.0 installation factor)	
(water supply tank with chiller 2,000 gal)	5,200
(solvent receiver tank FRP 6,000 gal)	8,800
(water receiver tank FRP 6,000 gal)	8,800
Total	236,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/man-year) (additionally, supervision is 25 percent of operator)	25,000
Maintenance (6 percent of capital cost)	14,200
Propane (4,942 gal at $1/gal)	5,000
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Disposal of condensed water Treatment (38,830 gal at $0.25/gal) Transportation (300 miles at $4/loaded mile x 8 loads)	19,300
Disposal of recovered solvent Treatment (58,000 lb at $0.42/lb) Transportation (785 miles at $3.50/loaded mile x 1 load)	27,100
Monitoring (52 samples; approximately $350 each)	18,000
Total	$ 112,000

TABLE A-4. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CARBON ADSORPTION/STEAM REGENERATION AT GWAS

Capital	Cost
Carbon adsorption/regeneration unit ($45,000 base unit x 2.5 installation factor) (air preheater at $500 installed)	$ 113,000
Portable steam generator (270 lb/hr at 9 psi; 8 boiler HP)	4,000
Stack test (1 test for particulates, HCl, NO$_x$, and organics)	15,000
Ancillary equipment (2.0 installation factor) (water supply tank with chiller 600 gal) (solvent receiver tanks not used due to water recycle and adequate solvent capacity in decanter)	3,400 N/A
Total	135,000

Operation and maintenance	Annual cost
Labor and supervision (1/4 operator at $40,000/man-year) (additionally, supervision is 25 percent of operator)	12,500
Maintenance (6 percent of capital cost)	8,100
Propane (189 gal at $1.25/gal)	200
Power (5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	2,000
Disposal of condensed water (None due to water recycle to stripper)	N/A
Disposal of recovered solvent Treatment (1,740 lb at $0.42/lb) Transportation (2,173 miles at $3.50/loaded mile x 1 load)	8,400
Monitoring (52 samples; approximately $350 each)	18,000
Total	$ 49,000

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TABLE A-5. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT SITE D (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($48,320)	120,800
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 136,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	8,200
Propane (584,000 gal at $0.50/gal)	292,000
Power (15 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	4,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 329,000

N/A = Not applicable.

TABLE A-6. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT SITE D (OPTION B WITH HEAT EXCHANGER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($232,680)	$ 581,700
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 597,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	35,800
Propane (146,000 gal at $0.50/gal)	73,000
Power (20 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	5,300
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 139,000

N/A = Not applicable.

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TABLE A-7. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT SITE D (OPTION C WITH HEAT EXCHANGER
AND OFF-GAS SCRUBBING)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($300,200)	$ 750,500
Stack test (1 test for particulates, HCl, NOx, and organics)	15,000
Total	$ 766,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	46,000
Propane (146,000 gal at $0.50/gal)	73,000
Power (20 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	5,300
Caustic trailer (lease tanker truck at $2,500/month)	30,000
Caustic supply (19,000 gal at $0.19/gal materials + 19,000 gal at 0.12/gal transport)	5,900
Total	$ 210,000

N/A ≐ Not applicable.

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TABLE A-8. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT SITE G (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($ 61,000)	$ 152,500
Propane feed system (18,000-gal propane tank, piping, transport hook-up vendor quote)	25,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 193,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	11,600
Propane (1,350,000 gal at $0.40/gal)*	540,000
Power (30 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	7,900
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 585,000

N/A = Not applicable.
*Fuel cost $0.40 because of volume discount.

TABLE A-9. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS FOR FUME INCINERATION AT SITE G (OPTION B - WITH HEAT EXCHANGER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($304,000)	$ 760,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 775,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	46,500
Propane (335,000 gal at $0.50/gal)	168,000
Power (30 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	7,900
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 247,000

N/A = Not applicable.

TABLE A-10. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS FOR FUME INCINERATION AT SITE G (OPTION C - WITH HEAT EXCHANGER AND OFF-GAS SCRUBBING)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($402,500)	$1,006,250
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$1,021,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	61,300
Propane (335,000 gal at $0.50/gal)	168,000
Power (50 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	13,200
Caustic trailer (lease tanker truck at $2500/month)	30,000
Caustic supply (55,000 gal at $0.19/gal materal + 55,000 gal at $0.12/gal transport)	17,100
Total	$ 340,000

N/A = Not applicable.

TABLE A-11. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS FOR FUME INCINERATION AT LTTS (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($50,120)	$ 125,300
Baghouse	10,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 150,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	9,000
Propane (290,000 gal at $0.41/gal)	118,900
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 156,000

N/A = Not applicable.

TABLE A-12. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT LTTS (OPTION B - WITH HEAT EXCHANGER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($230,300)	$ 575,800
Baghouse	10,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 601,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	36,100
Propane (72,270 gal at $0.41/gal)	29,700
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 94,000

N/A = Not applicable.

TABLE A-13.   DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT LTTS (OPTION C - WITH HEAT EXCHANGER
OFF-GAS SCRUBBER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($300,300)	$ 750,000
Baghouse	10,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 775,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	46,500
Propane (72,270 gal at $0.41/gal)	29,700
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer (lease tanker truck at $2,500/month)	30,000
Caustic supply (26,000 gal at $0.18/gal material + 26,000 gal at $0.05/gal transport)	6,000
Total	$ 165,000

N/A = Not applicable.

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TABLE A-14. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS FOR FUME INCINERATION AT GWAS (OPTION A – BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($39,160)	$ 97,900
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 113,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	6,800
Propane (138,700 gal at $0.45/gal)	62,400
Power (3 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	1,200
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 95,000

N/A = Not applicable.

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TABLE A-15. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR FUME INCINERATION AT GWAS (OPTION B - WITH HEAT EXCHANGER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($174,320)	$ 435,800
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 451,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	27,100
Propane (34,670 gal at $0.45/gal)	15,600
Power (5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	2,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 70,000

N/A = Not applicable.

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TABLE A-16. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS FOR FUME INCINERATION AT GWAS (OPTION C – WITH HEAT EXCHANGER AND OFF-GAS SCRUBBER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($227,840)	$ 596,600
Stack test (1 test for particulates, HCl, NO$_x$, and organics)	15,000
Total	$ 585,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	35,100
Propane (34,670 gal at $0.45/gal)	15,600
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer (lease tanker truck at $830 month)	10,000
Caustic supply (800 gal at $0.21/gal materials + 800 gal at $0.15/gal transport)	300
Total	$ 114,000

N/A = Not applicable.

TABLE A-17. DETAIL FOR APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR PURASIV PROCESS - GENERIC APPLICATION AT 10,000 CFM

Capital	Cost
PURASIV system (with auxiliary equipment and installation within battery limits)	$1,000,000 to 1,250,000

Operation and maintenance	Annual cost
Labor (1 operator, 4 shifts, $40,000/year)	$ 160,000
Supervision (25 percent of 1 supervisor, $40,000/yr)	10,000
Maintenance (6 percent of capital)	60,000 to 75,000
Propane (10 lb steam/lb solvent x 60 tons/yr x 2,000 lb/ton x 1,000 Btu/lb steam x 1 gal propane/91,500 Btu x $0.50/gal propane)	6,600
Power (20 hp x 0.75 kw/hp x 24 x 365 x $0.06/kwh)	7,900
Disposal of recovered solvent	10,000 to 50,000
Monitoring (52 samples, approximately $350 each)	18,000
Carbon replacement (5,000 lb/yr at $8/lb due to Cl-HC fouling)	40,000
Total (per year)	$ 300,000 to $ 400,000

[a]Costs are gross estimates based only on past operating
experience as conveyed by telephone communication with Union
Carbide. An installation factor of 2.0 to 2.5 was applied to
estimated equipment cost.

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TABLE A-18. DETAIL FOR APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR KPR/INCINERATION PROCESS - GENERIC APPLICATION
AT 3,200 CFM (FLOW OF ISV AT SITE D)

Capital	Cost
KPR adsorption/fume incineration (including ancillary equipment and installation)[b]	$ 760,000
Stack Test (1 test for particulates, HCL, NO_x, and organics)	$ 15,000
Total	$ 775,000

Operation and maintenance	Annual cost
Labor (1 operator at $40,000/year)	$ 40,000
Supervision (25 percent of 1 supervisor, $40,000/yr)	10,000
Maintenance (6 percent of capital)	45,600
Propane (0.576×10^6 Btu/hr x 24 x 365 x 1 gal propane/91,500 Btu x $0.50/gal propane)	27,600
Power (8.32 kw/hr x 24 x 365 x $0.04/kwh)	3,000
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 144,000

[a]Based on extropolation from 10,000 and 20,000 cfm, generic
 applications using 0.17 exponential scale-up factor.
[b]Installation factor of 2.5 was used due to grassroots
 installation at a remote location.

TABLE A-19. DETAIL FOR APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR KPR/INCINERATION PROCESS - GENERIC APPLICATION
AT 7,300 CFM (FLOW OF ISV AT SITE G)

Capital	Cost
KPR adsorption/fume incineration (including ancillary equipment and installation)[b]	$ 870,000
Stack Test (1 test for particulates, HCL, NO_x, and organics)	$ 15,000
Total	$ 885,000

Operation and maintenance	Annual cost
Labor (1 operator at $40,000/year)	$ 40,000
Supervision (25 percent of 1 supervisor, $40,000/yr)	10,000
Maintenance (6 percent of capital)	52,200
Propane (1.314 x 10^6 Btu/hr x 1 gal propane/ 91,500 Btu x 24 x 365 x $0.50/gal)	62,900
Power (19 kw x 24 x 365 x $0.04/kwh)	6,700
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 190,000

[a]Based on extropolation from 10,000 and 20,000 cfm, generic
applications using 0.17 exponential scale-up factor.
[b]Installation factor of 2.5 was used due to grassroots
installation at a remote location.

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TABLE A-20. APPROXIMATE[a] CAPITAL AND OPERATING COSTS FOR
KPR/INCINERATION PROCESS – GENERIC APPLICATION AT 1,864 CFM
(FLOW OF ISV AT LTTS)

Capital	Cost
KPR adsorption/fume incineration (including ancillary equipment and installation)[b]	$ 700,000
Stack Test (1 test for particulates, HCL, NO$_x$, and organics)	$ 15,000
Total	$ 715,000

Operation and maintenance	Annual cost
Labor (1 operator at $40,000/year)	$ 40,000
Supervision (25 percent of 1 supervisor, $40,000/yr)	10,000
Maintenance (6 percent of capital)	42,000
Propane (0.335 x 10^6 Btu/hr x 1 gal propane/ 91,500 Btu x 24 x 365 x $0.50/gal)	16,000
Power (4.84 kw x 24 x 365 x $0.06/kwh)	2,500
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 129,000

[a]Based on extropolation from 10,000 and 20,000 cfm, generic
applications using 0.17 exponential scale-up factor.
[b]Installation factor of 2.5 was used due to grassroots
installation at a remote location.

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TABLE A-21. APPROXIMATE[a] CAPITAL AND OPERATING COSTS FOR
KPR/INCINERATION PROCESS - GENERIC APPLICATION AT 800 CFM
(FLOW OF ISV AT GWAS)

Capital	Cost
KPR adsorption/fume incineration (including ancillary equipment and installation)[b]	$ 600,000
Stack Test (1 test for particulates, HCL, NO_x, and organics)	$ 15,000
Total	$ 615,000

Operation and maintenance	Annual cost
Labor (1 operator at $40,000/year)	$ 40,000
Supervision (25 percent of 1 supervisor, $40,000/yr)	10,000
Maintenance (6 percent of capital)	36,000
Carbon element replacement	10,000
Propane (0.144 mm Btu/hr x 1 gal/91,500 Btu x 24 x 365 x $0.50/gal)	6,900
Power (2.1 kw x 24 x 365 x $0.06/kwh)	1,100
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 122,000

[a]Based on extropolation from 10,000 and 20,000 cfm, generic
 applications using 0.17 exponential scale-up factor.
[b]Installation factor of 2.5 was used due to grassroots
 installation at a remote location.

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TABLE A-22. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT SITE D (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($65,000)	162,500
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO$_x$, and organics)	15,000
Total	$ 178,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	10,700
Catalyst replacement	1,000
Propane (833 gal/day x 365 days x $0.50/gal)	152,000
Power (15 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	4,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 193,000

N/A = Not applicable.

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TABLE A-23. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT SITE D
(OPTION B - WITH HEAT EXCHANGE)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($99,000)	247,500
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 263,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	15,800
Catalyst replacement	1,000
Propane (483 gal/day x 365 days x $0.50/gal)	88,200
Power (20 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	5,300
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 135,000

N/A = Not applicable.

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TABLE A-24.   DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT SITE D
(OPTION C - WITH HEAT EXCHANGE AND OFF-GAS SCRUBBING)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($359,000)	897,500
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO$_x$, and organics)	15,000
Total	$ 913,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	54,800
Catalyst replacement	1,000
Propane (483 gal/day x 365 days x $0.50/gal)	88,200
Power (20 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	5,300
Caustic trailer (lease tanker truck at $2,500/month)	30,000
Caustic supply (19,000 gal at $0.19/gal materials + 19,000 gal at $0.12/gal transport)	5,900
Total	$ 235,000

N/A = Not applicable.

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TABLE A-25. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT SITE G (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($96,000)	240,000
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 255,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	15,300
Catalyst replacement	1,000
Propane (1,890 gal/day x 365 days x $0.50/gal)	345,000
Power (30 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	7,900
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 394,000

N/A = Not applicable.

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TABLE A-26. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT SITE G
(OPTION B - WITH HEAT EXCHANGE)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($146,000)	365,000
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 380,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	22,800
Catalyst replacement	1,000
Propane (1,096 gal/day x 365 days x $0.50/gal)	200,000
Power (30 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	7,900
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 257,000

N/A = Not applicable.

TABLE A-27. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT SITE G
(OPTION C - WITH HEAT EXCHANGE AND OFF-GAS SCRUBBING)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($530,000)	$1,325,000
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$1,340,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	80,400
Catalyst replacement	1,000
Propane (1,096 gal/day x 365 days x $0.50/gal)	200,000
Power (50 hp at 0.75 kw/hp at $0.04/kwh x 24 hr x 365 days)	13,200
Caustic trailer (lease tanker truck at $2,500/month)	30,000
Caustic supply (55,000 gal at $0.19/gal materials + 55,000 gal at $0.12/gal transport)	17,100
Total	$ 392,000

N/A = Not applicable.

TABLE A-28. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS FOR CATALYTIC OXIDATION AT LTTS (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($50,000)	125,000
Baghouse	10,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 150,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	9,000
Catalyst replacement	1,000
Propane (262 gal/day x 365 days x $0.41/gal)	39,300
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 77,000

N/A = Not applicable.

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TABLE A-29. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT LTTS (OPTION B - WITH HEAT EXCHANGE)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($75,500)	188,800
Baghouse	10,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 214,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	12,800
Catalyst replacement	1,000
Propane (152 gal/day x 365 days x $0.41/gal)	22,800
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 65,000

N/A = Not applicable.

TABLE A-30. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT LTTS
(OPTION C - WITH HEAT EXCHANGE AND OFF-GAS SCRUBBING)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($275,500)	688,800
Baghouse	10,000
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 714,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	42,800
Catalyst replacement	1,000
Propane (152 gal/day x 365 days x $0.41/gal)	22,800
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer (lease tanker truck at $2,500/month)	30,000
Caustic supply (26,000 gal at $0.18/gal material + 26,000 gal at $0.05/gal transport)	6,000
Total	$ 156,000

N/A = Not applicable.

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TABLE A-31. DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT GWAS (OPTION A - BASE UNIT)

Capital	Cost
Incinerator (2.5 installation factor) base unit ($39,000)	97,500
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 113,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	6,800
Catalyst Replacement	1,000
Propane (198 gal/day x 365 days x $0.45/gal)	32,500
Power (3 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	1,200
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 67,000

N/A = Not applicable.

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TABLE A-32.   DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT GWAS
(OPTION B - WITH HEAT EXCHANGER)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger ($59,000)	147,500
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 163,000

Operation and maintenance	Annual cost
Labor and supervision (1/2 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 25,000
Maintenance (6 percent of capital)	9,800
Catalyst Replacement	1,000
Propane (115 gal/day x 365 days x $0.45/gal)	18,900
Power (5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	2,000
Caustic trailer	N/A
Caustic supply	N/A
Total	$ 57,000

N/A = Not applicable.

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TABLE A-33.   DETAIL OF ESTIMATED CAPITAL AND OPERATING COSTS
FOR CATALYTIC OXIDATION AT GWAS
(OPTION C - WITH HEAT EXCHANGER AND OFF-GAS SCRUBBING)

Capital	Cost
Incinerator (2.5 installation factor) with heat exchanger and scrubber ($220,000)	550,000
Baghouse	N/A
Stack test (1 test for particulates, HCl, NO_x, and organics)	15,000
Total	$ 565,000

Operation and maintenance	Annual cost
Labor and supervision (1 operator at $40,000/ manyear) (additionally, supervision is 25 percent of operator)	$ 50,000
Maintenance (6 percent of capital)	33,900
Catalyst replacement	1,000
Propane (115 gal/day x 365 days x $0.45/gal)	18,900
Power (7.5 hp at 0.75 kw/hp at $0.06/kwh x 24 hr x 365 days)	3,000
Caustic trailer (lease tanker truck at $830/month)	10,000
Caustic supply (800 gal at $0.21/gal material + 800 gal at $0.15/gal transport)	300
Total	$ 117,000

N/A = Not applicable.

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TABLE A-34. DETAIL OF APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR GENERIC APPLICATION OF UV/OZONE/CATALYTIC OXIDATION
AT 3,200 CFM (FLOW OF ISV AT SITE D)

Capital	Cost
UV/ozone/catalytic oxidation system (including ancillary equipment and installation)[b]	$ 310,000
Stack test	15,000
Permitting (engineering assistance)	---
Total	325,000

Operation and maintenance	Annual cost
Labor (1/2 operator at $40,000/year plus 25 percent of operator for supervision)	$ 25,000
Maintenance (6 percent of capital)	19,500
Power (0.4 kwh/1,000 scf x (3,200/1,000) scfm x 60 x 24 x 365 x $.04/kwh)	26,900
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 89,000

[a]Based on extropolation from 2,500 cfm, generic applications
using 0.86 exponential scale-up factor assumed equal to ozone
generator scale-up factor.
[b]Conservative installation factor of 2.5 used even though
it is a modular, all-electric unit due to the early level of
development.

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TABLE A-35. DETAIL OF APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR GENERIC APPLICATION OF UV/OZONE/CATALYTIC OXIDATION
AT 7,300 CFM (FLOW OF ISV AT SITE G)

Capital	Cost
UV/ozone/catalytic oxidation system (including ancillary equipment and installation)[b]	$ 633,000
Stack test	15,000
Permitting (engineering assistance)	---
Total	648,000

Operation and maintenance	Annual cost
Labor (1/2 operator at $40,000/year plus 25 percent of operator for supervision)	$ 25,000
Maintenance (6 percent of capital)	38,900
Power (0.4 kwh/1,000 scf x (7,300/1,000) scfm x 60 x 24 x 365 x $.04/kwh)	61,400
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 143,000

[a]Based on extropolation from 2,500 cfm, generic applications
using 0.86 exponential scale-up factor assumed equal to ozone
generator scale-up factor.
[b]Conservative installation factor of 2.5 used even though
it is a modular, all-electric unit due to the early level of
development.

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TABLE A-36. DETAIL OF APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR GENERIC APPLICATION OF UV/OZONE/CATALYTIC OXIDATION
AT 1,864 CFM (FLOW OF LTTS)

Capital	Cost
UV/ozone/catalytic oxidation system (including ancillary equipment and installation)[b]	$ 194,000
Stack test	15,000
Permitting (engineering assistance)	---
Total	209,000

Operation and maintenance	Annual cost
Labor (1/2 operator at $40,000/year plus 25 percent of operator for supervision)	$ 25,000
Maintenance (6 percent of capital)	12,600
Power (0.4 kwh/1,000 scf x (1,864/1,000) scfm x 60 x 24 x 365 x $.06/kwh)	23,500
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 79,000

[a]Based on extropolation from 2,500 cfm, generic applications
using 0.86 exponential scale-up factor assumed equal to ozone
generator scale-up factor.
[b]Conservative installation factor of 2.5 used even though
it is a modular, all-electric unit due to the early level of
development.

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TABLE A-37. DETAIL OF APPROXIMATE[a] CAPITAL AND OPERATING
COSTS FOR GENERIC APPLICATION OF UV/OZONE/CATALYTIC OXIDATION
AT 800 CFM (FLOW OF GWAS)

Capital	Cost
UV/ozone/catalytic oxidation system (including ancillary equipment and installation)[b]	$ 93,000
Stack test	15,000
Permitting (engineering assistance)	---
Total	108,000

Operation and maintenance	Annual cost
Labor (1/4 operator at $40,000/year plus 25 percent of operator for supervision)	$ 12,500
Maintenance (6 percent of capital)	6,500
Power (0.4 kwh/1,000 scf x (800/1,000) scfm x 60 x 24 x 365 x $.06/kwh)	10,100
Monitoring (52 samples, approximately $350 each)	18,000
Total (per year)	$ 47,000

[a]Based on extropolation from 2,500 cfm, generic applications
using 0.86 exponential scale-up factor assumed equal to ozone
generator scale-up factor.
[b]Conservative installation factor of 2.5 used even though
it is a modular, all-electric unit due to the early level of
development.

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